Comments Received during the Public Review Period on the "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009"

Commenter: Dan Heintz, Director, ASES Programs, Air Liquide

Comment: *Based on its experience and knowledge of the hydrogen industry, Air Liquide sees a need for better understanding of how the draft US Inventory Report accounts for GHG emissions from hydrogen production and further requests that future US GHG Inventory Reports more clearly address GHG emissions from hydrogen production. Recently, the industrial gases industry commissioned a study of its GHG emissions for the years 2007 and 2008. The study shows that industrial gas hydrogen production resulted in between 13.5 and 14.5 million metric tons per year of direct GHG emissions in 2007 and 2008. We have studied the current GHG Inventory Draft and have not been able to identify where these emissions are accounted for. The following steps were undertaken but do not resolve this question:*

- *Chapter 3 Energy covers the wide range of energy-related emissions categories, including fuel production at refineries, which would appear on its face to include hydrogen production.*
- *Section 3.7 Petroleum Systems does not include a hydrogen source category.*
- *Section 3.1 Fossil Fuel Combustion could possibly include hydrogen production, more specifically perhaps as part of the Combustion Industrial subgroup.*
- *The emission estimation methodology for Fossil Fuel Combustion at Annex 2, Part 2.1 indicates that emissions from certain activities are subtracted from the fossil fuel combustion sector fuel totals (see Annex 2.1, Steps 2 and 4). However, hydrogen production is not identified as one of the reasons for subtracting emissions from the combustion emissions totals.*
- *The Energy Information Administration (EIA) Monthly Energy Review is cited as the source for the fuel consumption data. A review of the most recent publication (http://www.eia.doe.gov/mer/pdf/mer.pdf) does not appear to provide information that could demonstrate whether hydrogen production is included.*

In the Draft Report, GHG emissions from hydrogen production may or may not be captured in GHG emissions attributed to petroleum systems or industrial combustion. Even if those emissions are in fact included in the overall emissions inventory, they are an undifferentiated subset of some sector's emissions. Air Liquide believes that the US emissions inventory should provide accurate data regarding GHG emissions from hydrogen production for several reasons. Providing a more accurate industry profile through better defined emission categories would benefit all users of the data. Accurate representation of the proportion of emissions from independent hydrogen production facilities is necessary given the size and rapid growth of the emission source. In addition, accurate baseline emission data for hydrogen production (and perhaps other sectors now subsumed into other reporting categories) in the US Inventory Report will ensure that increased efficiencies are recognized and producers and the US are appropriately credited for any emission reduction efforts. Air Liquide would like to confirm that

GHG emissions from hydrogen production facilities are included in the inventory and to recommend the establishment of a subcategory for hydrogen production be explored, given the nature and size of this source.

Commenter: Karin Ritter, Manager, Regulatory and Scientific Affairs, American Petroleum Institute (API)

(See Attachment A for referenced tables).

Sections 3.6 (Natural Gas Systems) and 3.7 (Petroleum Systems)

Comment: *Some significant changes have been made to specific emission factors in the inventory this year. We anticipate that the inventory will continue to change and be refined as companies begin reporting under the GHG Reporting Program (GHGRP). As a result, we are concerned that revisions to the inventory this year will be misinterpreted to imply significant under reporting of specific emission sources. We request that EPA reformat the presentation of information provided in the inventory to appropriately reflect current emission reduction activities. Further details are provided below.*

Emission Reductions

Comment: *The most significant issue with EPA's 2009 national inventory is that the national emission factors do not account for activities widely used by industry to reduce* CH_4 *emissions. EPA indicates (page A-150) that "accounting for* CH_4 *reductions reported to the Natural Gas STAR Program and* CH_4 *reductions resulting from regulations, such as the National Emissions Standards for Hazardous Air Pollutants (NESHAP) regulations* is done after *the total national inventory is compiled." (emphasis added). EPA provides the total sector emission reductions in Tables A-125 and A-126, for Natural Gas STAR and regulatory driven reductions, respectively. However, the reductions shown are not split by emission source type. Not clearly identifying the reductions associated with each emission source, consistent with the presentation of emission factors by source, implies that the sources emit larger quantities of GHG than they actually do. Emission reductions for many of the inventory source types, especially the sources which were revised as a part of the 2009 inventory (e.g., gas well cleanups) are significant.*

Comment: *EPA also indicates that "Before incorporating the reductions into the Inventory, quality assurance and quality control checks are undertaken to identify errors, inconsistencies, or irregular data. The checks include matching Natural Gas STAR reported reductions to specific inventory sources to make sure that a reported reduction for one source is not greater than the emission estimate for that source. This check has lead (sic) to emissions updates to sources such as well completions and workovers, and well clean up." This implies that if EPA Natural Gas STAR emission reductions are greater than EPA's national estimate of emissions for a particular source, then EPA inflates the national emission result, presumably by inflating the emission factor, so that the reduction does not produce a negative emission. EPA indicates that such an adjustment was made to the completion, workover, and well clean up emission factors, but does not elaborate on the method or significance of the adjustments. This also indicates that EPA has the information available to report the reductions for each individual* *emission source. The result is that the emission factors reported by EPA are artificially inflated to balance out the Natural Gas STAR reductions, and do not account for significant emission reduction and emission controls. The inflated national emission factors may result in a false conclusion that emissions from some of the source types (particularly those that EPA has recently modified) have been significantly underestimated in the past. For full transparency and a realistic representation of the industry operational practices, EPA's reported emission factor for each source type should account for the emission reduction practices and regulatory impacts within each region.*

Comment: *To further investigate the transparency of the reported Natural Gas STAR reduction data, the 2009 CH_4 reductions in Table A-125 of the draft 2009 national inventory attributed to EPA Natural Gas STAR were compared to the Gas STAR paper, EPA Natural Gas STAR Program Accomplishments for 2009, as shown in Table 1 [See Table 1 on page 3 of Attachment A]. As shown, the 2009 CH_4 emission reductions reported in the draft EPA national inventory attributed to Gas STAR are higher than the reductions reported in the Gas STAR accomplishments paper, and the differences are not explained. EPA should clearly document the differences and explain the basis for the values provided in Table A-125.*

Gas Well Workovers

Comment: *For the 2009 inventory, EPA split gas well workovers into two emission sources: conventional gas well workovers and unconventional gas well workovers. EPA classifies unconventional wells as those involving hydraulic fracturing, and notes in the Technical Support Document (TSD) associated with 40 CFR 98 Subpart W2 that "it is understood that not all unconventional wells involve hydraulic fracturing, but some conventional wells are hydraulically fractured, which is assumed to balance the over-estimate." Industry commented on the proposed Subpart W that the terms "conventional" and "unconventional" were confusing and not commonly used by industry. For consistency and clarity, EPA should adopt the terminology used in the final Subpart W (i.e., with and without hydraulic fracturing). While the emission factors for conventional (without hydraulic fracturing) gas well workovers are on the same order of magnitude as the "well workover" factors that were used in the 2008 inventory, the unconventional (with hydraulic fracturing) well workover factors are over three thousand times larger, which seems to be excessively overestimated with no applicable documentation. Table 2 compares the 2008 and 2009 workover emission factors by region [See Table 2 on page 4 of Attachment A].*

Comment: *The national inventory does not describe how EPA determined the emission factors for conventional gas well workovers. However, the TSD indicates an emission factor for well workovers from the EPA/GRI study is applied for conventional wells. The emission factor provided in the EPA/GRI study is 2,454 Mcf of methane/workover. Minor adjustments to this emission factor are believed to be reflected in Table 2 to account for different methane compositions in each region [See Table 2 on page 4 of Attachment A]. For unconventional well workovers, the TSD indicates that the emission factor is assumed to be the same as unconventional well completions. An analysis of the unconventional completion emission factor and emission estimates is provided in the following section.*

Comment: *As noted previously, EPA adjusts the total national inventory for emission reductions reported through the Gas STAR program and reductions that results from regulatory requirements, such as NESHAP. Hence, it is also not possible to determine which of the emission reductions shown in Table A-125 and A-126 are attributed unconventional well workovers, as the tables do not split reductions by activity.*

Unconventional Well Completions

Comment: *As a part of the 2009 inventory, "unconventional well completions" is added as a new emission source to the "Drilling and Well Completion" inventory category. Unconventional well completions now account for approximately 7% of the total natural gas production* CH_4 *emissions, where as in 2008, "well drilling" emissions accounted for approximately 0.07% of total natural gas production* CH_4 *emissions. EPA's inventory documentation does not reference the source of information for the reported counts of wells drilled and unconventional completions. The only statement is that "the Inventory tracks activity data for unconventional well counts (which we assumed to be completed by hydraulic fracture for the purposes of this analysis) in each region." EPA should indicate which of the numerous references listed for activity data are associated with the individual emission sources, particularly if activity data are derived from other information.*

Comment: *The regional emission factors used for unconventional gas well completions are the same as those used for unconventional gas well workovers (shown in Table 2). The emission factors for unconventional gas well completions are much larger than the emission factors for well drilling; as noted for well workovers. EPA justifies the use of larger emission factors due to the higher pressure venting of gas used to drive large volumes of liquid from the production well.*

Comment: *As mentioned for unconventional well workovers, EPA does not describe how the emission factor for unconventional gas well completions was developed. For unconventional completions, the TSD associated with 40 CFR 98 Subpart W indicates the emission factor was derived from participant information shared and presented at Natural Gas STAR technology transfer workshops. EPA cites two Gas STAR presentations as the source of information for the unconventional well completion/workover emission factor. The TSD for Subpart W provides further details on the data specifically used in developing the Subpart W average emission factor of 9,175 Mscf/completion. It is assumed that the emission factors shown in Table 2 vary from the Subpart W average emission factor due to different gas compositions in the region, but this is not documented in the inventory.*

Comment: *Table 3 summarizes the information presented in the two Gas STAR presentations referenced in the 2009 national inventory and demonstrates the basis for the average emission factor [See Table 3 on page 5 of Attachment A].]. API notes the following based on reviewing the information in Table 3: • EIA clearly indicates that the volumes reported are vented and flared emissions combined. EPA is assuming the total volume of gas is vented, which inflates the emission factor. It is also interesting that although EIA reports this information annually, EPA only evaluated the 2002 data presented in the Gas STAR report.*

Comment: *EPA did not use the information provided by the second (unidentified) source. This data set shows a wide spread of recovered gas volumes and percentages. As this was presented* *at a Gas STAR workshop, it would be useful if EPA could request more details on this data from the source of the information.*

Comment: *It is not clear why EPA did not include the information presented by BP. The BP data point represents a controlled completion and would support the development of a controlled emission factor.*

Comment: *The Williams data provides the total amount of gas generated from completions. However, the Williams presentation provides data that demonstrates the majority of this gas is recovered, and the small amount that is not recovered is either vented or flared. In fact, using the data Williams provides, which demonstrates the actual emissions that result accounting for emission reduction activities, produces an average emission factor of approximately 2,000 Mscf/well, which is about onefifth of the emission factor used in EPA's inventory.*

Comment: *For this source it is not clear where EPA may adjust the emissions to account for emission reduction activities or regulatory requirements, such as flaring. EPA notes "some states, such as Wyoming, may require that natural gas produced during well completions not be vented. In these regions emissions from natural gas well completions and re-completions are either recovered for sales or must be flared. The volume of gas recovered by bringing equipment to the wellsite for the treatment and injection of the produced completion gas into the sales pipeline is reported by Natural Gas STAR. The remaining volume of completion gas from states that do not allow the venting of this gas is flared". The inventory includes a source "completion flaring" but EPA does not discuss how this source relates to the unconventional completion emissions.*

Comment: *The number of completions flared does not appear to have changed, and in fact is slightly larger for 2009 compared to 2008. This indicates that EPA has not made a significant adjustment to the accounting for emissions from completion flaring. However, it would seem that some portion of the unconventional completion emissions would be flared and should thus be represented in the source category for completion flaring. EPA should reflect the actual flared and vented emissions, as represented by current industry practices, by appropriately accounting for completion emissions that are vented versus flared and eliminating the artificial inflation of the emission factor and potential double counting of some completion activities.*

Well Clean Ups (LP gas wells)

Comment: *In the 2009 inventory, the total emissions from "well clean ups" account for approximately 51% of the total natural gas production sector CH_4 emissions. For comparison, in the 2008 inventory, well clean up emissions accounted for approximately 6% of the total natural gas production CH_4 emissions, when not accounting for emission reductions due to Natural Gas STAR or other regulations. EPA notes that the methodology for quantifying emissions from this source category was revised to include a large sample of well and reservoir characteristics from the HPDI database of production and permit information along with an engineering equation to estimate the volume of natural gas necessary to expel a liquid column choking the well production. The approach used for the emission factor is based on a fluid equilibrium calculation to determine the volume of gas necessary to blow out a column of liquid for a given well pressure, depth, and casing diameter.*

Comment: *EPA notes in Section 3.6 that the HPDI database for well production and well properties was queried to obtain sample data on average well depth, shut-in pressure, well counts, and well production rates from each basin. Although EPA does not state explicitly, it is implied that differences in these characteristics across basins account for the regional differences reported in the inventory. For complete transparency, EPA should publish the equation and the average characteristics used for each basin.*

Comment: *Emission reductions for this source type are significant. EPA even notes that emission reductions may be under reported in the Planned Improvements portion of Section 3.6, and that the potential for emission reductions from gas well cleanups to be underestimated will be investigated in the next Inventory cycle. The Natural Gas STAR Lessons Learned for installing plunger lift systems reports emission reduction ranging from 4,700 to 18,250 Mscf/yr. In addition, the West Coast emission factor, the second largest of the regional factors, clearly does not account for the practices in California, where petroleum producers have strict emission controls on* CH_4*. EPA describes in Annex 3.4 that some states may require that natural gas produced during well completions not be vented; in these regions the natural gas is recovered to sales or flared. The natural gas from gas well clean ups can also be recovered to sales or flared. Alternatively, if gas and liquids/water are piped separately to the surface from a gas well, and any artificial lift method (not just plunger lift) was applied to bring the liquids to the surface, then there would be no venting of gas and liquids from the well from liquids unloading. All such artificial lift practices and other methods for reducing emissions should be clearly identified in EPA's inventory. The inventory should provide separate factors for controlled and uncontrolled activities, as is done for condensate tanks.*

Flashing Losses from Oil and Condensate Tanks

Comment: *The 2009 national inventory includes an adjustment to the condensate tank emission factors for the Mid-Central and South West regions for both condensate tanks without control devices and condensate tanks with control devices. EPA noted in Section 3.6 that the 2009 inventory includes, for the first time, data from a Texas Environmental Research Consortium (TERC) study (TERC 2009) which provided a small sample of data representing two regions in Texas where separator dump valve malfunctions were detected and measured. The TERC study measured emissions rates from several oil and condensate tanks in Texas. These data were plotted and compared to flashing emissions simulated via E&P Tanks. EPA observed that the E&P Tanks results indicated additional emissions beyond flashing losses were present in approximately 50 percent of the tanks and concluded that the emissions may be attributed to separator dump valves malfunctioning or other methods of associated gas entering the tank and venting from the roof. It is not clear how EPA applied the TERC study data to determine the 2009 emission factors. The TERC study specifically addressed Volatile Organic Compounds (VOC) emissions from oil and condensate storage tanks, and also provided vent sample data, including for methane. The TERC study was designed to specifically capture all of the emissions from each tank, and therefore it is unlikely that half of the tanks measured would have missed emissions. In addition, the TERC study did not capture all of the input data necessary to run E&P Tanks (e.g., pressurized separator liquid compositions). Therefore, it seems more likely that the "additional emissions" resulting from EPA's simulation runs of the flashing emissions are actually a result of assumptions EPA used to assign the model input parameters.*

Comment: *Furthermore, the E&P Tanks modeling EPA is referencing does not incorporate dump valve malfunctions as an emission parameter in the model algorithm. If EPA wishes to accurately quantity emissions from separator dump valve malfunctions, testing should be performed to specifically focus on emissions from malfunctioning dump valves. The activity factors for condensate tanks did not vary significantly from 2008 to 2009. However, EPA does not clearly identify how the throughput is differentiated between tanks with and without control devices. Instead, it appears that the same throughput is being applied to each tank type, presumably based on an assumption that 50% of tanks are controlled. EPA should clearly identify what source was used to obtain the throughput information for each tank type.*

Centrifugal Compressors

Comment: *The 2009 inventory includes for the first time emission factors for centrifugal compressors by seal type (wet and dry seals, respectively) for the natural gas processing and natural gas transmission sectors. Table 4 compares the 2008 and 2009 emission factors and equipment counts by sector [See Table 4 on page 9 of Attachment A]. As shown in Table 4, the emission factors for centrifugal compressors increased from 2008 to 2009, regardless of seal type. The resultant emissions increase was most significant in the gas processing sector. Table 4 also shows that the activity factors for compressors have been split into compressors with wet and dry seals. However, EPA does not clearly identify how the counts of compressors were allocated between wet and dry seals or what information source EPA used to make this allocation. An EPA Natural Gas STAR Lessons Learned paper on replacing wet seals with dry seals notes that about 90 percent of all new compressors come with dry seals. It is anticipated that the number of centrifugal compressors with wet seals will decrease over time as centrifugal compressors with wet seals are replaced by centrifugal compressors with dry seals.*

Comment: *EPA notes that the centrifugal compressor emission factors were revised as a part of the 2009 Natural Gas STAR paper on replacing wet seals with dry seals and a Methane to Markets study of measurements at four gas processing plants. The WGC report notes that "Methane to Markets experience, combined with another assessment of four natural gas facilities, has identified measurements from 48 wet seal centrifugal compressors, with methane emissions totaling 14,860 thousand m3 methane/year. The data, which show that seal oil degassing rates for individual compressors could range from 0 to 2,756 thousand m3/year, can be divided into two groups: a low-emitting group (33 compressors) and a high-emitting group (15 compressors). The low emitters have an average emission rate of 26 thousand m3 methane/year for a single compressor. The high emitters have an average emission rate of 934 thousand m3 methane/year for a single compressor." inventory based on guidance from a World Gas Conference paper (WGC, 2009), which gathered 48 sample measurements of centrifugal compressor wet seal oil degassing emissions and published the results. The World Gas Conference paper, which is cited as the source of the 2009 inventory emission factors, is actually in turn citing a combination of data provided in the*

Comment: *The basis of the EPA wet seal emission factors is not clear and is inconsistent with Subpart W of the EPA's Mandatory Reporting Rule. Subpart W, §98.233(o)(7), presents a default wet seal compressor emission factor of 12.2 million scf methane/yr (at 68°F and 14.7 psia), which converts to 33,425 scfd/compressor – consistent with the data presented in the WGC* *report. The values used for the 2009 EPA inventory are much higher, at 51,370 scfd/compressor for processing, 50,222 scfd/compressor for transmission, and 45,441 scfd/compressor for storage. EPA does not provide documentation to explain the basis for the differences among the industry sectors. The Subpart W default emission factor for wet seal compressor degassing is based on 14,860 thousand m3 methane/yr from the World Gas Conference paper divided by 43 centrifugal compressors (EPA Technical Support Document, 2010). Note that denominator is 43 compressors rather than all 48. The Technical Support Document indicates that five of the 48 wet seal centrifugal compressors were found to not be emitting10; thus the emission factor is incorrectly averaged only over the leaking compressors and does not account for the fact that a portion of the compressor seals do not leak, thus the total number of compressors (i.e. 48) ought to be included when deriving the emission factor.*

Comment: *Table 5 of the Methane to Markets paper presents a comparison of the emission factors measured during the study to the EPA/GRI 1996 emission factors. The average factor measured for compressor seals was 0.852 kg THC/h/source, while the EPA/GRI (1996) study average factor was actually larger by about 30%, at 1.172 kg THC/h/source. Footnote 4 to Table 5 notes that the "compressor seals component category accounts for emissions from individual compressor seals. As compressor seal leakage was typically measured from common vent and drain lines, emissions have been divided evenly among the seals on units with detected leakage." The factors are not split by wet or dry seals. As Appendices I and II (containing site specific field measurement data) are missing to protect business confidentiality, it is not possible to determine whether the study further separates compressor seal measurements into wet and dry seals. EPA does not directly cite a source for the updated dry seal emission factors, but provides in the References section for the Natural Gas Systems a reference to the Natural Gas STAR paper discussed above. The executive summary of the paper notes that dry seals emit up to 6 scfm; on page 4 of the paper it is noted that dry seals emit less during normal operation (0.5 to 3 scfm across each seal, depending on the size of the seal and operating pressure). The cost savings in Exhibit 5 are calculated assuming 2 dry seals at a total of 6 scfm.*

Comment: *If EPA is citing the Natural Gas STAR paper as the reference for the dry seal emission factor, it can be assumed that the emission factor derived from such data will be on an order of magnitude similar to that provided in the reference document. It can conservatively be assumed that the emissions will be estimated using the maximum leakage rate (6 scfm), instead of the normal operation leakage rate (0.5 to 3 scfm). However, when converting the 6 scfm identified in the Natural Gas STAR paper to a scfd basis, as is used in the 2009 inventory, the factor should be around 8,640 scfd/compressor on a natural gas basis, even lower on a methane basis, and+E81 significantly less than the factor shown in the 2009 inventory for natural gas processing (25,189 scfd/compressors), transmission (32,208 scfd/compressors), and storage (31,989 scfd/compressors). EPA should explain these differences and clearly state the reference of the emission factors for each segment.*

National Energy Modeling System (NEMS) Regions

Comment: *EPA notes that the regions are divided in accordance with the National Energy Modeling System. However, according to EIA, the NEMS regions are: Pacific, Mountain, West North Central, East North Central, New England, Middle Atlantic, South Atlantic, East South Central, and West South Central. EPA should clearly identify which of the NEMS regions are* *included in each of the natural gas production regions (North East, Mid-Central, Rocky Mountain, South West, West Coast, and Gulf Coast). In addition, Texas (the state for which the TERC study was conducted) falls into one NEMS region: West South Central. Yet in the 2009 inventory, the condensate storage tank emission factors for both the Mid-Central and South West regions were revised. EPA notes in Section 3.6 that because the TERC dataset was limited to represent production from only 14 counties that represent 0.5 percent of U.S. production, the national emission factor was scaled up such that only production from these counties is affected by the occurrence of associated gas venting through the storage tank. EPA should clearly identify how the factors for both the Mid-Central and South West regions were adjusted. If Texas does fall within both the Mid-Central and South West regions, and if the factors were truly scaled according to the counties affected, the factors should not be identical for both Mid-Central and South West regions.*

Updated API Compendium

Comment: *API provided comment on the draft 1990 – 2008 inventory that, as indicated above, API revised the API Compendium in 2009. References to emission factors from the API Compendium should be updated to reflect the 2009 version of API's Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry. For example, Section 3.7 Petroleum Systems (p. 3-51, line 15) and Annex 3.5 Petroleum Systems (p. A-168, line 34) reference "API (2004)", but should instead reference the newest version of the API Compendium as the source of the asphalt blowing emission factor.*

Asphalt Blowing

Comment: *API provided comment on the draft 1990 – 2008 inventory that the most significant change noted in the 2008 national inventory was the addition of asphalt blowing* CO_2 *emissions for refineries in the Petroleum Systems category. This emission source accounted for 36% of the total non-combustion* CO_2 *emissions from petroleum systems in 2008, and accounts for 31% of the total non-combustion* CO_2 *emissions from petroleum systems in 2009.*

Comment: *The* CH_4 *factor for asphalt blowing in the 2009 EPA Inventory of Greenhouse Gas Emissions and Sinks is the same as is used in the 2008 EPA Inventory of Greenhouse Gas Emissions and Sinks. As a part of API's comments on the draft 1990 – 2008 inventory, API also noted that neither emission factor is consistent with the 2009 API Compendium. The 2009 Compendium+E86 presents the same factor as the 2004 API Compendium, which is the cited source of the emission factor used in the EPA Inventory of Greenhouse Gas Emissions and Sinks. The 2009 API Compendium cites a simple emission factor for uncontrolled asphalt blowing from AP-42 (EPA, AP-42, Section 5.1.2.10, 1995). The AP-42 emission factor for asphalt blowing is assumed to be on an air-free basis (AP-42 does not specify this, but notes the factor represents "emissions"). Asphalt blowing exhaust composition data (13 mol%* CH_4 *and 9 mol%* CO_2*, on an air free basis) presented in an Oil & Gas Journal article12 is applied to derive the* CH_4 *and* CO_2 *emission factors of 5.55E-4 tonnes* CH_4*/bbl asphalt blown and 1.01E-3 tonnes* CO_2*/bbl asphalt blown, respectively. (Further details on the derivation of these emission factors are provided in Appendix B of the 2009 API Compendium.) For comparison, the EPA emission factors converted to a similar basis are 4.9E-5 tonnes* CH_4*/bbl and 1.09E-3 tonnes* CO_2*/bbl. However, the primary distinction between the API Compendium emission factors and those used in the*

EPA inventory is the units of measure applied to the activity factor. The API emission factors are based on the volume (or mass) of asphalt blown, while the EPA emission factors appear to be based on the total volume of asphalt produced (411 Mbbl/cd production). As a result, the EPA emission factors result in much higher emission estimates.

Refining Emissions

Comment: *There are a number of sources that do not appear to be included in the national GHG inventory. For the refining sector, these include CO_2 emissions from flares, hydrogen production, catalytic cracking units, fluid coking units, catalytic reforming units, sulfur recovery units, and coke calcining units. Emissions from each of these sources are required to be reported under the GHGRP, and for which EPA had to assess the emissions as part of the justification for their inclusion in the regulation. The inventory should incorporate EPA's current understanding of these emissions or document why they are excluded from the inventory.*

Alignment with the EPA GHG Reporting Program

Comment: *EPA indicates in the Planned Improvements portion of both of Sections 3.6 (Natural Gas Systems) and 3.7 (Petroleum Systems) that data collected through 40 CFR Part 98 (Mandatory Reporting of Greenhouse Gases; Final Rule) will be used as a source for potential improvements to the inventory. API supports the continued improvement of the national inventory, but urges EPA to provide transparent justification and formal technical review for the changes. In Section 3.6 (page 3-48, line 25) EPA notes that reporting will begin in 2010 for natural gas suppliers. EPA is referring to reporting under Subpart NN (Suppliers of Natural Gas and Natural Gas Liquids) for local distribution systems. However, Subpart NN only requires reporting of volumes and emissions associated with potential end-use combustion of the natural gas and the natural gas liquids supplied. The information reported under Subpart NN does not represent actual emissions, and if the gas supplied were to be combusted their emissions would fall under Section 3.1 (Fossil Fuel Combustion), not to Section 3.6.*

Comment: *EPA should clarify that data collection begins for Subpart NN in 2010, with emissions reported beginning in 2011 for calendar year 2010. In addition, if EPA is implying that emissions reported under Subpart W will be used to improve the Natural Gas Systems inventory, EPA should clarify that data collection for Subpart W begins in 2011, with emission reporting beginning in 2012 for calendar year 2011.*

Comment: *In Section 3.7 (page 3-52, line 37) EPA notes that U.S. petroleum refineries will be required to calculate and report their greenhouse gas emissions beginning in 2010. EPA should clarify that data collection begins for petroleum refineries in 2010, with emissions reported beginning in 2011 for calendar year 2010.*

Section 3.6 and Annex 3.4, Natural Gas Systems

Comment: *The changes to the emission factors for gas well workovers, gas well cleanups, well completions, condensate storage tanks, and centrifugal compressors should all be documented in Section 3.6 and Annex 3.4, as discussed above. Many other emission factors also changed from 2008 to 2009; a few examples are provided in Table 5 [See Table 5 on page 14 of Attachment A]. One example is provided for each region except West Coast, for which the emission factor revisions are due to rounding differences between the two inventories. Note that the table below* *is not all inclusive of the emission factor revisions. The reasons for all emission factor revisions should be documented in the inventory, not just the reasons for major emission factor revisions.*

Annex 3.4 Natural Gas Systems

Comment: *Emission factors and activity factors are only provided for 2008 (with the exception of "key activity data drivers" provided in Table A-124), yet emissions are shown for multiple years. API recommends adding emission and activity factors for all years for which emissions are being estimated, for full disclosure. (In addition, it is discussed in Step 1 that activity factors vary by year.)*

Comment: *If emission factors determined for 1995 are assumed to be representative of emissions from each source type over the period 1990 through 2009, API recommends adding that information to Step 1 or Step 3, similar to the text in Annex 3.5 Petroleum Systems, p. A-168, line 21. Alternatively, if emission factors are not assumed to be representative of emissions from each source type over the period 1990 through 2009, this should be noted as well, and emission factors should be added for all years for which emissions are being estimated, for full disclosure.*

Comment: *p. A-150, Step 1, Second Paragraph, Line 3) The reference to "Table A-123" should instead be to "Table A-124".*

Comment: *Multiple Tables- Where tables are split onto multiple pages, EPA should add table header for each continued page.*

Comment: *Table A-123- Emission factor units for Mishaps (Dig-ins) should be "Mscfy/mile" instead of "mscfy/mile", to be consistent with the other units presented in the annex.*

Comment: *Table A-125- API recommends adding a note that indicates "Totals may not sum due to independent rounding."*

Annex 3.5 Petroleum Systems

Comment: *Emission factors and activity factors are only provided for 2009, yet emissions are shown for multiple years. API recommends adding emission and activity factors for all years for which emissions are being estimated, for full disclosure. (In addition, it is discussed in Step 2 that activity factors vary by year.)*

Section 3.7 Petroleum Systems,

Comment: *Tables 3-43, 3-46, and 3-47- API recommends adding a note that indicates "Totals may not sum due to independent rounding."*

Comment: *Table 3-43- The values shown for Tank Venting for 2005, 2006, and 2008 should be 0.2 Tg CO_2 Eq., not 0.3 Tg CO_2 Eq. This change corresponds with the values shown in Table A-142 for Tank Venting. API recommends verifying the values.*

Comment: *Table 3-47- The totals shown appear to vary more than would be due to rounding error. For example, the 2008 total should be approximately 43,410 Gg, but is shown as 43,311 Gg. API recommends verifying the totals.*

Comment: *Tables 3-43 and 3-46- Where tables are split onto multiple pages, EPA should add the table header for each continued page.*

Comment: *Tables A-136 through A-138, and Table A-14- API recommends adding a header row above the last four columns noting "2009 EPA Inventory Values", similar to the table presentation for Annex 3.4 (Natural Gas Systems).*

Comment: *p. A-170, Table A-137- Remove the period after "bbl" in the units for the emission factor and activity factor for Heaters.*

Comment: *p. A-170, Table A-138, and p. A-172, Table A-141- API recommends spelling out "cd" for emission factors with units of "cd refinery feed" or "cd feed".*

Comment: *p. A-170, Table A-137- API recommends formatting with the Activity Factor for the Marine Loading and Pump Stations activity factors. The Marine Loading activity factor appears to have a digit (4) on the row below; the Pump Station activity factor does not clearly show all digits.*

Comment: *p. A-169- API recommends mentioning Table A-140, and how the values presented are used in calculation of the* CO_2 *emissions presented in Annex 3.5.*

Comment: *p. A-171, Table A-139) API recommends adding a note that indicates "Totals may not sum due to independent rounding."*

Comment: *p. A-172, Table A-142) The value shown for Production Field Operations should be 317 instead of 319, which affects the total row in Table A-142 (the total should be 461 Gg instead of 463 Gg) and the values shown in Table 3-43 and Table 3-44.*

Annex 3.4 Natural Gas Systems, and Annex 3.5 Petroleum Systems

Comment: *Multiple table references have a space before the table number. Tables are currently referenced as "Table AX" and should be "Table A-X".*

Peter D. Robertson, Senior Vice President for Legislative and Regulatory Affairs, America's Natural Gas Alliance

Comment: *To ensure the accuracy and credibility of the inventory, ANGA urges EPA to work collaboratively with industry and other stakeholders to develop a more robust methodology for estimating emissions from well cleanup and unconventional well completions and workovers before including new emissions estimates from these sources. ANGA urges EPA to respond to the critical issues we have identified below and provide more information on the data and assumptions that were not specifically identified in the Draft Inventory or its appendices.*

Emission Estimates from Natural Gas Field Production

Comment: *EPA Has Dramatically Increased Emission Estimates from Natural Gas Field Production: We are concerned about changes that have been made in calculating emissions from natural gas field production. The Draft Inventory contains new methodologies and assumptions for estimating emissions from natural gas field production that dramatically increase the emissions estimated from this sector. EPA's previous national inventory estimated 2008 emissions from natural gas field production at 14.1 Tg CO_2 Eq.1 Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008 (2010 Inventory), Table 3-37. In the new Draft Inventory, estimated emissions in 2008 are 122.9 Tg CO_2 Eq, an increase of 108.8 Tg CO_2 Eq. To put this in perspective, the new draft estimate for natural gas field production is nearly 9 times higher than the previous estimate, more than double the previous estimate for all natural gas system emissions (which also includes processing, transmission and storage, and distribution) and on its own represents 1.5 percent of the 2011 draft national emissions inventory. No other emission source underwent such a striking adjustment. ANGA supports adjustments to the methodologies and assumptions used to estimate emissions in the national inventory, but only insofar as they are supported by new, robust data and reasonable methods of calculation. These requirements are heightened in the case of EPA's new estimates for natural gas field production, given the magnitude of the changes. Nearly 95 percent of the increased emissions estimates for 2008 are attributable to two changes: (1) a new methodology for natural gas well cleanups accounts for 66 percent of new emissions and (2) the inclusion of emissions from unconventional wells (shale gas and coal bed methane) accounts for 28 percent.*

Comment: *ANGA is concerned that at least two elements of the EPA's Draft Inventory – revised emissions estimates from natural gas well cleanups and new emissions estimates from "unconventional" well completions and workovers – rely on fundamentally flawed data and analysis. Given the magnitude of the new emissions estimated from these sources – the Draft Inventory repeatedly highlights that they are the largest sources of emission increases in the inventory – we believe that EPA must provide a more robust analytical justification. Failing to do so is counterproductive to EPA's mission to provide reasonable, scientifically sound information and could lead policymakers, scientists and others relying on the inventory to draw incorrect conclusions about greenhouse gas emissions from the natural gas sector and the greenhouse gas benefits of natural gas relative to other sources of energy.*

Emissions from Natural Gas Well Cleanups

Comment:*: The majority of increased emissions from natural gas field production come from a change in the methodology for estimating emissions from natural gas well liquid unloading, also referred to as cleanups in the Draft Inventory. The new methodology contains a critical flaw in its failure to include emission reductions from the use of artificial lift systems, such as plunger lifts, and raises a number of other concerns. Artificial lift systems provide substantial reductions in emissions from liquid unloading but it does not appear that EPA accounts for their use in the inventory. Generally, venting of gas during lift cycles is an old practice that has been largely replaced with methods that capture the gas. In addition to plunger lift systems – which can eliminate emissions entirely – there are a number of technologies used to reduce or eliminate venting from unloading, including but not limited to: • Velocity string (install smaller diameter tubing to increase the velocity); • Compression (reduce tubing pressure); • Pumps; • Gaslift (added gas to boost flow above critical); • Foaming (soap sticks, back side soap injection, cap* *string); • Injection systems (inject water below packer); and • Venting/Stop Clocking/Equalizing (temporary methods that are used in some cases). The omission of emission reductions from the application of these practices results in a worst-case scenario approach that is not appropriate for an emissions inventory and dramatically overestimates the emissions from natural gas production. It is not enough to adjust the inventory by results from the Natural Gas STAR program since not all natural gas producers are Natural Gas STAR partners and not all Natural Gas Star partners report all emission reduction activities. In fact, artificial lift may be under-reported even among Natural Gas STAR Partners as it is part of producing a well and not looked at as an emissions reduction technology.*

Comment: *EPA appears to have developed the methodology based on two sources. The first source, an EPA/Natural Gas STAR report "Lessons Learned: Installing Plunger Lift Systems in Natural Gas Wells", provides an equation for estimating the volume of gas vented during a blowdown. EPA has not indicated whether the equation or the results were adjusted for the purposes of the Draft Inventory, nor has EPA provided the data, or average characteristics, that it used in the equation. EPA states that it used its other source, production and permit data obtained from HPDI in October 2009, for at least part of the data to run the equation. HPDI supplied information on well depth, shut-in pressure, well counts and well production data. However, more detail on the data actually used, particularly the data used to calculate shut-in pressure (which is needed to ensure that EPA focused on low pressure wells where liquid unloading is more prevalent), is necessary to adequately evaluate the methodology and results. The equation only provides the volume vented for each blowdown. To complete the inventory, EPA needs to know how many wells required cleanups (Wc) and how many blowdowns are required annually at those wells (BDa) so that: U.S. Methane Emissions from Cleanups = Wc*BDa*Vv*0.7886. The documentation for the inventory does not indicate what data were used to estimate Wc or BDa. While the HPDI data would have provided the total number of wells, it is unlikely that HPDI's production data would have provided information on which wells perform cleanups and the number of blowdowns performed each year at those wells. EPA has recently estimated these two variables. Appendix B of the Technical Support Document (TSD) developed in support of Subpart W of the Mandatory Greenhouse Gas Reporting Rule uses data from a 1992 survey conducted by the Gas Research Institute (GRI) to estimate that 41.3 percent of conventional wells require cleanups. The 1992 survey was of 25 well sites.*

Comment: *To determine the average number of blowdowns at each well, the TSD uses a simple average of 31 blowdowns per well based on publicly available data from two Natural Gas STAR partners: 1. BP recovered 4 Bcf of emissions using plunger lifts with automation to optimize plunger cycles on 2,200 wells in the San Juan basin. Using the equation for blowdown emissions, EPA determined that 51 blowdowns per well would be required to match the reported 4 Bcf of emissions. 2. ExxonMobil reported it recovered 12 MMcf using plunger lifts on 19 wells in Big Piney. ANGA asks EPA to clarify whether it used these same assumptions – 41.3 percent of conventional wells require liquid unloading and these wells require 31 blowdowns annually – for the Draft Inventory. If the Agency did not use these assumptions, we ask that it supply this information so that stakeholders can provide comment. If the Agency did use the TSD assumptions, then ANGA notes that the blowdown estimate is based on two isolated data points and does not appear to account for well-specific variables, such as differences in well depth (shallow wells such as those in the San Juan Basin require more blowdowns than deep wells),* *that drive the number of necessary blowdowns. If EPA has developed additional assumptions for determining the number of blowdowns, including well-specific data, it should disclose them and provide an opportunity for comment.*

Emissions from Unconventional Well Completions and Workovers

Comment: *According to Table A-120, which provides region specific emission estimates, the Draft Inventory uses emission factors ranging from 7,194 Mcf/completion to 8,630 Mcf/completion. While this suggests some modifications from the TSD that EPA should clarify, it appears that the Draft Inventory largely utilizes the same methodology and data points since two presentations are the only referenced sources. This raises a number of concerns. Not only is the emission factor based on four data points with the high end nearly 30 times higher than the low end, a fatal flaw in itself, but none of these data points were purported to be representative estimates of emissions from completions or workovers. Rather, they are case studies from a voluntary EPA program aimed at reducing emissions and, as such, they are simply reporting the results of a handful projects in the field. They are not based on standardized and audited protocols. Moreover, case studies, by their nature, are typically based on the "cream-of-crop" projects. Since in this context, the best projects are the ones that reduce the greatest amount of emissions, using emission reductions from those case studies as the basis for a national inventory can lead to grossly inaccurate results. The bottom line is that EPA has the methodology backwards: the Agency should evaluate the volumes that are emitted from non-green completion activities rather than rely on green completion volumes from a voluntary program that were never intended to provide inventory-grade information to the Agency.*

Comment: *We note that even the data point that was not based on green completions (the EIA data used for the 6,000 Mcf/completion estimate) raises serious concerns. First, when backing out emissions attributable to conventional well completions and workovers, the TSD uses the old emission factors for conventional wells and assumes the rest is attributable to unconventional wells. The TSD provides no support in the EIA data for this assumption, nor does EPA explain why it uses an old emissions factor that has been revised in the TSD. Based on the lack of data, a more reasonable approach would be to adjust based on the fraction of conventional wells – 40 percent. Making this adjustment, conventional wells would be responsible for 18 Bcf, leaving 27 Bcf to unconventional wells. The TSD then applies all remaining emissions to completions, instead of first adjusting for workovers (the 45 Bcf applies to completions and workovers, but the TSD emissions estimate is for completions only). For example, according to data in the TSD, there were 13,403 unconventional well completions and workovers in 2007 and of these, 31 percent were workovers. After this adjustment, 18.6 Bcf are attributable to unconventional well completions. Dividing that by the number of completed wells yields an average emission rate of approximately 2,350/Mcf per completion – substantially less than half the estimate in the TSD. This provides further support to the conclusion emissions from unconventional well completions and workovers have been significantly overestimated.*

Comment: *Moreover, the emissions estimates assume that all of the gas is vented and none of it is flared. In discussing the effects of the new emissions estimates on inventories, the TSD assumed that about half of the wells would flare their emissions. This assumption itself is suspect, since it is based on an oversimplification of state regulations and not on industry practice. But it appears that the Draft Inventory may compound this by not assuming any flaring* *for unconventional completions or workovers – if flaring reductions are included, they are not readily identifiable. Our experience indicates that, while the amount of flaring will vary depending on state regulations and specific operational characteristics of the well, in many U.S. fields sending gas to flare is relatively easy and preferred to venting strictly for safety reasons (this is particularly true for sour gas). Coupled with state regulations requiring flaring or emissions controls (e.g. in Louisiana and Wyoming), failing to adequately account for flaring in the inventory will lead to an inaccurate estimate of emissions from completions and workovers. Accordingly, we ask EPA to clarify its flaring assumptions and provide further opportunity for comment.*

Comment: *Finally, the Draft Inventory indicates that activity data were used, but does not specify the source or reference the data. The Draft Inventory also assumes that the emissions from completions and workovers are the same without providing an explanation on how these two different processes result in the same emissions. EPA should provide the activity data and an explanation of its assumption that emissions from completions and workovers are the same and provide an opportunity for stakeholder comment on this information.*

Commenter: Fiji George, Carbon Strategies Director, El Paso Corporation

Well Clean up (Low Pressure Gas Wells)

Comment: *The US EPA has not accounted for the use of all artificial lift techniques in reducing or eliminating emissions.*

Comment: *EPA does not indicate if the minimum volume or if an adjustment was made to account for potentially longer vent times in its computational methods.*

Comment: *For complete transparency, EPA should publish the average characteristics used in its computational methods for each basin.*

Comment: *EPA used statistically insignificant dataset to make a massive change in emission rates to represent the entire industry.*

Comment: *The most significant issue with the approach applied to quantify low pressure well clean up emissions, and also a universal issue with EPA's national inventory, is that the national emission factors do not account for activities widely used by industry to reduce CH_4 emissions. If gas and liquids/water are piped separately to the surface from a gas well, and any artificial lift method (not just plunger lift) was applied to bring the liquids to the surface, then there would be no venting of gas and liquids from the well from liquids unloading.*

Comment: *EPA must account for contribution and use of all such artificial lift practices in the emissions from liquids unloading activity and must revise its total emissions in a manner it provides a reasonable reflection of industry practices.*

Well Workovers and Completions

Comment: *EPA has made some undocumented increases in the emission factor for workovers.*

Comment: *EPA proposes that higher pressure frack fluid results in higher natural gas emissions. This conclusion has no documented basis.*

Comment: *EPA should indicate which of the numerous references listed for activity data are associated with the individual emission sources.*

Comment: *EPA has made some undocumented increase in the emission factor for workovers/completions to account for emission reductions that are subtracted from the inventory totals.*

Comment: *EPA should indicate which of the numerous references listed for activity data are associated with the individual emission sources, particularly if activity data are derived from other information.*

Comment: *EPA cites two Gas STAR presentations as the source of information for the unconventional well completion/workover emission factor. This is a statistically insignificant dataset to extrapolate to support for such a large increases for the entire industry.*

Comment: *EPA is assuming the total volume of gas is vented, which inflates the emission factor.*

Comment: *EPA has made some undocumented increase in the emission factor for completions to account for emission reductions that are subtracted from the inventory totals, when in actuality the regional emission factors reported in the inventory are somewhat less than the average value shown in.*

Comment: *EPA should reflect the actual flared and vented emissions, as represented by current industry practices, by appropriately accounting for completion emissions that are vented versus flared, and eliminate the artificial inflation of the emission factor and potential double counting of some completion activities.*

Comment: *The unconventional completion and workover emission factors are inflated by more than 4 times.*

Condensate Tanks

Comment: *EPA does not account for emission reductions from the Natural Gas STAR and NESHAP programs and may have assumed a malfunction condition that results in inflated emission factors.*

Comment: *The percentages of control shown do not account for emission reductions reported through the Natural Gas STAR Program or associated with NESHAP Regulations.*

Comment: *These emissions may be attributed to separator dump valves malfunctioning or other methods of associated gas entering the tank and venting from the roof.*

Comment: *Comparing the TERC study results to the E&P Tank model results could result in drawing an incorrect conclusion because it assumes that the model runs accurately estimates the flashing losses.*

Comment: *If EPA wishes to accurately quantity emissions from separator dump valve malfunctions, testing or modeling should be performed to quantify emissions from tank flashing with and without malfunctioning dump valves, instead of an approach that compares measured data to a model.*

Comment: *EPA should clearly identify how the factors for both the Mid-Central and South West regions were adjusted. If Texas does fall within both the Mid-Central and South West regions, if the factors were truly scaled according to the counties affected, the factors should not be identical for both Mid-Central and South West regions.*

Comment: *The* CO_2 *emission factor does not mention the range of condensate production gravities from the HPDI database that were used to improve the methane emission factor.*

Comment: *It is recommended that EPA adopt this approach for other activities within the national inventory (e.g., well completions, well workovers, well clean ups, and compressor wet and dry seals), as described in the other sections of this report.*

Centrifugal Compressors

Comment: *EPA has over-estimated the emissions for the processing sector by approximately 10.4% and the total inventory for the transmission/storage sector by approximately 4.2% due to incorrect averaging of the main data source.*

Comment: *If the emission factor calculated by using the correct average of the WGC data had been used in the draft inventory, then the emissions due to wet seal compressors would be reduced to 58% of the current estimate for processing, 60% of the current estimate for transmission, and 66% of the current estimate for storage. This would reduce the total inventory for the processing sector by approximately 10.4%, and the total inventory for the transmission/ storage sector by approximately 4.2%.*

General

Comment: *Given the extremely large changes that EPA has made in some categories from the previous published inventories, EPA should have provided all of the background data. In many cases, EPA has failed to provide the background information or data necessary to properly vet or test many of the alleged increased emissions. Neither the DRAFT inventory nor the Federal Register notice refer to the EPA's Mandatory Reporting Rule Subpart W Technical Support Document (TSD), which shaped the emissions estimates from certain sources that allegedly, contributed to the largest changes.*

Comment: *We are also very concerned that the EPA, in the haste of finalizing the inventory by April 15, 2011 will not have sufficient time to fully analyze and consider our comments. A revision of this magnitude to the inventory from the gas sector, when actual measured data is* *now being collected under requirements of Subpart W, seems unnecessarily hasty and potentially counter-productive. Some NGOs and certain members of the press have already begun to draw conclusions from some of the unvetted changes that EPA has made in this proposed inventory.*

Comment: *We are also concerned that the DRAFT inventory may become the basis for other mandatory reduction policies or rules currently being drafted by the EPA. Considering the far reaching implications, and since the goal is to "get the numbers sufficiently right", we urge the EPA should to wait until real data is available in March 2012 and in the meantime revert back to the 2008 methods, rather than making unsubstantiated changes this year based on very limited data or ignoring the substantial reductions already undertaken by industry.*

Commenter: Fredrick I. Rippee, PE

Comment: *Hello Leif, It scares me that the EPA is about to increase regulations pertaining to the so-called climate change that appears to merely be alchemy created by some scientists bent on increased funding of their personal projects. The rest of the ethical scientists appear not to be on board with this alchemy. A short lesson in American history regarding her might will show that fossil fuel based manufacturing is the source of that might and economic prowess. A simple poll in world politics will show that the rest of society is belly laughing at how American bureaucrats blindly destroy American might - while the world ignores the 'climate change problem' - so that the net result is American stature is self destroyed while the world hysterically moves forward polluting through no control whatsoever to make their products that are ultimately sold in America. Those+E10 foreign products contribute factors of times more pollution to 'the planet' in foreign countries - countries grateful to the EPA for single handedly destroying American industry and moving the jobs, wealth and manufacturing overseas and out of EPA bullying reach. For what, I ask? Because we can? Do you really want to go down in history as the sonofbitches that finally did what the Soviets could not do - crush America? I don't believe that the EPA really gives a tinker's damn about realistic and balanced environmental regulation. If you did, you would do one simple and effective act: you would mandate that the US-wide incompetence of the holistic inability of city engineers to properly set traffic lights would be corrected. Look at your own data. A simple fix of setting traffic lights to ensure that traffic would remain at speed, following Newton's law that a body in motion tends to stay in motion unless acted upon by an external force, would enjoy minimal fuel consumption and, therefore, minimal 'climate change' gas production. It is a published fact that acceleration and idling of motor vehicle engines creates many times more 'climate change' gas than a vehicle at speed being maintained at speed. I have queried several city engineers and it is amazing how often these traffic stops are dictated by the engineers' boss to appease the mayor, city counsel, or other political abuse of power wielder, such that the entire town is forced to stop in front of their drapery - or other such similar - business in an unethical attempt to foster traffic from the street's stopped captive audience into their business. Therefore, that the EPA ignores their residential 'climate change' factor - the millions of unnecessary stoppages, idling, and accelerations due to traffic light incompetence - just signifies to me that this is a political blanket of feces designed to kill the American way of life through killing her industrial might. The EPA considers it a crime against nature to drop any petrochemicals, including fuel and lubricants,* *onto the ground: the very ground from which those petrochemicals came. Additionally, the EPA mandates monitoring and tight control of petrochemical discharge into the atmosphere by virtually all industry and motor vehicles. We might have to breathe that. They are even considering regulating lawn mowers, for crying out loud. What's next, mammal flatulence? Regardless, the whole world fleet of major airliners atomize tens of thousands of pounds of petrochemicals into the atmosphere every day in the name of flight safety. Yes, it is a shame to waste all of that fuel. However, it goes to prove that purposeful atomization of those petrochemicals has daily literally flown in the face of EPA bemoaning, and, golly gee, Wilbur, 'the planet' seems to be doing just fine. My BS meter looks like a fan. I don't understand, you say? I am a degreed chemical engineer, have a professional chemical engineering license in two states, and have been working as a chemical engineer for over 30 years. I think I might get it. I implore you to give the Idaho salute to the loud mouthed ignoramuses eating granola, hugging trees and crapping in the woods and do your American duty of promoting growth in America by imposing on industry only those regulations that make a significant and real difference as balanced by the cost in jobs and might. The Love Canal regulations would fall in that set. 'Climate change' regulations would not.*

Commenter: Jorge Verde

Comment: *Dear EPA, You have no business wasting my time and money monitoring CO_2 or any other greenhouse gases. Your agency is more dangerous to the welfare and livelihood of people in this country than Islamic Terrorism. S., Jorge Verde, Pawtucket, RI*

Comment: *The epa should stay out of it. CO/CO_2 is not a pollutant. Nothing you can do will substantially alter it. Stop spending my money on this boondoggle. Your agency should be cut 90%.*

Commenter: Juanita Nicholson

Comment: *Please do everything in your power to protect our country's environment by regulating greenhouse gases. Everyone, whether Democrat or Republican, needs clean air to breathe!*

Commenter: National Alliance of Forest Owners (NAFO)

Comment: *NAFO supports EPA’s use of the IPCC Guidelines in the GHG Inventory. Not only do the IPCC Guidelines produce meaningful data that can be compared over time and across countries, they also distinguish biomass emissions and fossil fuel emissions and demonstrate unequivocally that biomass is a carbon neutral energy source. Despite some calls for EPA to* *adopt a different accounting method for biomass energy combustion, NAFO encourages EPA to continue its current practice which produces accurate and efficient GHG data for the forestry sector.*

Commenter: Cynthia A. Finley, Director, Regulatory Affairs, National Association of Clean Water Agencies (NACWA)

Comment: *NACWA believes that the Inventory emission calculation methods for nitrous oxide could still be improved to more accurately reflect actual emissions from POTWs. The Draft Inventory calculates nitrous oxide emissions using estimated nitrogen loadings to wastewater that are based on reported annual protein consumption, which is the method used in the Intergovernmental Panel on Climate Change (IPCC) protocol document1 (IPCC Guidelines). NACWA believes these loading rates are too high, and that EPA needs to conduct more research to determine more accurate loading rates to use in the Inventory. As NACWA has pointed out in its previous comments on the Inventory, the rates currently used in the Inventory are higher than rates presented in standard wastewater engineering references such as Metcalf & Eddy. Metcalf & Eddy reports a per capita nitrogen loading rate to wastewater of 15 g N/capita-day, a value usually considered the "industry standard" by POTWs. This value is supported by a wealth of data and has been widely confirmed in U.S. practice. The type of data used in Metcalf & Eddy represents all domestic sources of nitrogen, including meal production and consumption, the use of other nitrogen-containing compounds, and both residential and commercial sources. EPA states in the Draft Inventory that "the dataset previously provided by NACWA was reviewed to determine if it was representative of the larger population of centralized treatment plants for potential inclusion into the inventory." However, EPA concluded that "this limited dataset did not represent the number of systems by state and the service populations served in the United States." NACWA disagrees with this conclusion. The survey of measured nitrogen loading rates at POTWs illustrates that the Metcalf & Eddy loading rate is representative of U.S. POTWs, as are other published loading rates cited in NACWA's previous comments. NACWA recommends that EPA conduct its own study of nitrogen loading rates to centralized treatment plants. EPA should have enough data available through its National Pollution Discharge Elimination System (NPDES) permitting program to determine an appropriate and justifiable nitrogen loading rate. The NPDES permitting program is nationwide in scope and long-term in nature, which would allow changes to be made in emissions estimates over the time series represented in the Inventory. Since EPA believes that further data of a broader and more representative scope are required before changing the Inventory, the NPDES database would certainly suffice as it represents every POTW in the U.S. NACWA believes that using the literature nitrogen loading values or EPA-collected values from U.S. POTWs would better reflect the actual emissions from POTWs than the current methods based on the IPCC Guidelines, which do not necessarily reflect actual conditions at POTWs throughout the nation. This is illustrated by the emission factor ("EF1") of 3.2 g N_2O/person-year for plants with no intentional denitrification, which is used in the Inventory and IPCC Guidelines to calculate nitrous oxide emissions from centralized wastewater treatment plants. This value was obtained from a single study of a very small wastewater treatment plant (1.06 million gallons per day, or MGD) in a small university town in New Hampshire. The population of this town is 12,500* *during the school year, but drops to 6,200 in the summer months, during which most of the measurements for this study were made. If the IPCC can use this single study to define an emission factor that is used for centralized treatment facilities all over the world, certainly EPA can justify changing the nitrogen loading rate for facilities in the U.S. based on literature values and data that it can collect from POTWs across the nation.*

Comment: *In the $N_2O_{EFFLUENT}$ equation (line 45, page 8-13), the USPOP factor should be multiplied by the WWTP factor, as it is in the $N_2O_{WOUT\ NIT/DENIT}$ equation, since septic system users should not be included in the amount of effluent discharged to aquatic environments. NACWA recommends that any nitrous oxide contributions from septic systems be calculated in a separate equation if they are to be included in the Inventory.*

Comment: *The value of 271 Tg N for N_{SLUDGE} (line 46, page 8-15) appears to be an error, resulting in a negative value for $N_2O_{EFFLUENT}$. The value of 144 Gg N found in the Draft Inventory Annex in Table A-206 (page A-254) is a more appropriate magnitude. However, even substituting this 144 Gg N value for N_{SLUDGE} does not result in a N_{TOTAL} value that agrees with the value of 16.2 Gg N_2O in Table 8-7. EPA must review the equation for $N_2O_{EFFLUENT}$ and all of the values used in it for accuracy.*

Commenter: Patricia Brewer, Acting Chief, Air Resources Division, National Park Service

Comment: *Now that EO 13514 has directed federal agencies to develop GHG inventories, there are now two different national inventories of GHG emissions in existence, and they are not formatted to be comparable. The Department of Energy-Federal Energy Management Program (FEMP) Federal GHG Accounting Guide was used for the first time in January 2011 for Federal agencies to submit 2008 baseline and 2010 inventories. The DOE-FEMP guidance uses the same IPCC guidelines as EPA, but because the inventory formats are so different, it is almost impossible to compare the results of the EPA Inventory with the DOE-FEMP submittals. EPA's Draft U.S. GHG Emissions & Sinks organizes the inventory by source category and sector and does not use the terms followed by the FEMP inventory: "scope 1, 2, or 3," "FEMP," "Federal GHG Accounting," or "Executive Order 13514." The DOE-FEMP GHG Accounting Guidance inventories report emissions by Scopes 1, 2, and 3, which are based on federal or contractor responsibility rather than by source category. The DOE-FEMP inventory does not refer to the EPA inventory categories. Since the Executive Order 13514 has made more people aware of GHG emissions and efforts to inventory them, it would be helpful to discuss in the draft EPA inventory how or whether the DOE-FEMP GHG Accounting Guidance relates to the U.S. GHG Emissions & Sinks Inventory.*

Commenter: Claudio H. Ternieden, Assistant Director of Research, Water Environment Research Foundation (WERF)

(See Attachments B and C for referenced reports)

Determining the N2O Generation Potential of Wastewater

Comment: *Page 8-7 - Line 27/28 "The principal factor in determining the $_{N2O}$ generation potential of wastewater is the amount of N in the wastewater" WERF suggests the following clarification of the above statement to read: "the principal factors in determining N_2O generation potential are the amount and variability of influent N-loading to a plant and the operating conditions of the plant itself". This clarification is important because WERF has conducted studies at wastewater treatment plants (WERF Report U4R07a Interim Report Greenhouse Gas Emissions from Wastewater Treatment Operations (2010)) [see Attachment B for this report] and found that wastewater treatment operations (over loaded and under-designed plants across numerous process configurations) generated higher levels of N_2O than some other differently-designed and operated BNR facilities, which generated very little N_2O. Variability in the generation of N_2O across BNR and other treatment plants is considerable. In other words, the "amount of N in the wastewater" is not "[t]he principal factor in determining the N_2O generation potential of wastewater" by itself, but that operating conditions of the plant itself is an important component in the determination of the appropriate N_2O generation potential of wastewater.*

Domestic Wastewater N2O Emission Estimates

Comment: *Page 8-14 - Lines 41 – "Approximately 7 grams N_2O is generated per capita per year if wastewater treatment included intentional nitrification and denitrification"; and Line 47- "Plants without intentional nitrification/denitrification are assumed to generate 3.2 grams N2O per capita per year." Based on our study (WERF Report U4R07a Interim Report Greenhouse Gas Emissions from Wastewater Treatment Operations (2010)) [see Attachment B for this report], WERF discourages EPA from using these single emission factors as identified in Lines 41 and 47 of page 8-14. Our study identified such variability in N_2O emissions from our set of monitored wastewater plants - both those with nitrification and denitrification and those considered conventional activated sludge processes- that identifying single factors or averages such as these are statistically inappropriate and could be rendered meaningless from data that does not exhibit central tendency according statistical principals.*

Comment: *Page 8-17- Line 33 "Such data will be reviewed to determine if a country-specific N_2O emission factor can be developed". WERF appreciates that the Agency is reviewing our two reports: 1) on N_2O emissions from municipal wastewater treatment systems (WERF Report U4R07a) [see Attachment B for this report]; and 2) on greenhouse gas emission from septic systems (WERF Report DEC1R09 Evaluation of Greenhouse Gas Emissions from Septic Systems (2010) [see Attachment C for this report]. Both reports contain a lot of new data. The N_2O generation report will be released as a final report with more facility data by the end of 2011. However, we are concerned that the Agency is still supporting a single, country-specific emissions factor based on the nitrogen present in the wastewater, although our study shows that operations also affect N_2O generation and emission, therefore rendering a country-specific emissions factor potentially meaningless.*

Attachment A

Attachment A

Karin Ritter
Manager

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March 25, 2011

Mr. Leif Hockstad and Mr. Brian Cook
U.S. Environmental Protection Agency, Climate Change Division (6207J)
1200 Pennsylvania Ave., NW
Washington, DC 20460
hockstad.leif@epa.gov and cook.brianb@epa.gov

Re: Review of EPA's Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009

Dear Sirs:

The American Petroleum Institute (API) appreciates the opportunity to offer input to the US EPA on the draft 1990-2009 US inventory of greenhouse gas (GHG) emissions (referred to as the 2009 national inventory).

As you know, API represents about 400 companies involved in all aspects of the oil and natural gas industry throughout the USA and globally. Over nearly a decade, API has developed an extensive record of ongoing activities related to GHG emissions estimation and reporting, and its guidelines are used worldwide for developing corporate GHG emission inventories for all segments of the oil and natural gas industry. This experience includes:

- Production of the *Petroleum Industry Guidelines for Reporting Greenhouse Gas Emissions (*IPIECA/OGP/API, December 2003, revised version expected Fall 2011);
- Development of the API *Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry* ('Road Test' version April 2001; Revised February 2004, Revised August 2009); and
- Participation in the Expert 'Cadre' of the US Technical Advisory Group (TAG) to the International Standards Organization (ISO).

Our comments are organized to focus first on the most significant inventory changes and API's most significant comments. Additional recommendations and editorial revisions follow.

Some significant changes have been made to specific emission factors in the inventory this year. We anticipate that the inventory will continue to change and be refined as companies begin reporting under the GHG Reporting Program (GHGRP). As a result, we are concerned that revisions to the inventory this year will be misinterpreted to imply significant under reporting of specific emission sources. We request that EPA reformat the presentation of information provided in the inventory to appropriately reflect current emission reduction activities. Further details are provided below.

1. Significant Inventory Revisions and Issues

1.1 Emission Reductions

The most significant issue with EPA's 2009 national inventory is that the national emission factors do not account for activities widely used by industry to reduce CH_4 emissions. EPA indicates (page A-150) that "*accounting for CH_4 reductions reported to the Natural Gas STAR Program and CH_4 reductions resulting from regulations, such as the National Emissions Standards for Hazardous Air Pollutants (NESHAP)*[1] *regulations* <u>*is done after*</u> *the total national inventory is compiled.*" (emphasis added). EPA provides the total sector emission reductions in Tables A-125 and A-126, for Natural Gas STAR and regulatory driven reductions, respectively. However, the reductions shown are not split by emission source type. Not clearly identifying the reductions associated with each emission source, consistent with the presentation of emission factors by source, implies that the sources emit larger quantities of GHG than they actually do. Emission reductions for many of the inventory source types, especially the sources which were revised as a part of the 2009 inventory (e.g., gas well cleanups) are significant.

EPA also indicates that "*Before incorporating the reductions into the Inventory, quality assurance and quality control checks are undertaken to identify errors, inconsistencies, or irregular data. The checks include matching Natural Gas STAR reported reductions to specific inventory sources to make sure that a reported reduction for one source is not greater than the emission estimate for that source. This check has lead (sic) to emissions updates to sources such as well completions and workovers, and well clean up*." This implies that if EPA Natural Gas STAR emission reductions are greater than EPA's national estimate of emissions for a particular source, then EPA inflates the national emission result, presumably by inflating the emission factor, so that the reduction does not produce a negative emission. EPA indicates that such an adjustment was made to the completion, workover, and well clean up emission factors, but does not elaborate on the method or significance of the adjustments. This also indicates that EPA has the information available to report the reductions for each individual emission source.

The result is that the emission factors reported by EPA are artificially inflated to balance out the Natural Gas STAR reductions, and do not account for significant emission reduction and emission controls. The inflated national emission factors may result in a false conclusion that emissions from some of the source types (particularly those that EPA has recently modified) have been significantly underestimated in the past. For full transparency and a realistic representation of the industry operational practices, EPA's reported emission factor for each source type should account for the emission reduction practices and regulatory impacts within each region.

To further investigate the transparency of the reported Natural Gas STAR reduction data, the 2009 CH_4 reductions in Table A-125 of the draft 2009 national inventory attributed to EPA Natural Gas STAR were compared to the Gas STAR paper, *EPA Natural Gas STAR Program Accomplishments for 2009,* as shown in Table 1. As shown, the 2009 CH_4 emission reductions reported in the draft EPA national inventory attributed to Gas STAR are higher than the reductions reported in the Gas STAR accomplishments paper, and the differences are not

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[1] 40 CFR 63 Subpart HH regulates glycol dehydrators, flashing losses, and fugitives.

explained. EPA should clearly document the differences and explain the basis for the values provided in Table A-125.

Table 1. Comparison of 2009 Methane Emission Reductions from EPA Inventory and Natural Gas STAR

Industry Sector	**Table A-125 of Draft 1990-2009 EPA GHG Inventory (Gg/yr)**	**Gas STAR Program Accomplishments (Original units, Bcf/yr)**	**Gas STAR Program Accomplishments (Converted to Gg/yr [a])**
Production	1,993	70	1,318
Processing	83	3.7	69.7[b]
Distribution	367	10.7	201.5[c]
	41	2.1	39.6
Total	2,484	86	1,629

[a] Converted from standard cubic feet to mass assuming standard conditions of 14.7 psia and 68°F.
[b] Includes processing and gathering.
[c] Includes transmission but the Gas STAR paper is not clear whether storage is included.

1.2 Gas Well Workovers

For the 2009 inventory, EPA split gas well workovers into two emission sources: conventional gas well workovers and unconventional gas well workovers. EPA classifies unconventional wells as those involving hydraulic fracturing, and notes in the Technical Support Document (TSD) associated with 40 CFR 98 Subpart W[2] that "*it is understood that not all unconventional wells involve hydraulic fracturing, but some conventional wells are hydraulically fractured, which is assumed to balance the over-estimate.*" Industry commented on the proposed Subpart W that the terms "conventional" and "unconventional" were confusing and not commonly used by industry. For consistency and clarity, EPA should adopt the terminology used in the final Subpart W (i.e., with and without hydraulic fracturing).

While the emission factors for conventional (without hydraulic fracturing) gas well workovers are on the same order of magnitude as the "well workover" factors that were used in the 2008 inventory, the unconventional (with hydraulic fracturing) well workover factors are over three thousand times larger, which seems to be excessively overestimated with no applicable documentation. Table 2 compares the 2008 and 2009 workover emission factors by region.

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[2] EPA, Greenhouse Gas Emissions Reporting From the Petroleum and Natural Gas Industry, Background Technical Support Document, November 9, 2010.

Table 2. Comparison of Well Workover Emission Factors for 2008 and 2009.

Region	2008 Well Workovers		2009 Conventional Wells		2009 Unconventional Wells	
	Emission Factor, scf/workover	Count of Workovers	Emission Factor, scf/workover	Count of Workovers	Emission Factor, scf/workover	Count of Workovers
North East	2,463	7,595	2,612	7,997	7,694,435	0
Mid Central	2,584	3,602	2,604	3,793	7,672,247	1,328
Rocky Mountain	2,447	3,848	2,442	4,299	7,194,624	2,342
South West	2,507	1,655	2,507	1,807	7,387,499	1,374
West Coast	2,861	74	2,861	78	8,429,754	0
Gulf Coast	2,757	3,019	2,759	3,265	8,127,942	0
Total		**19,793**		**21,239**		**5,044**

The national inventory does not describe how EPA determined the emission factors for conventional gas well workovers. However, the TSD indicates an emission factor for well workovers from the EPA/GRI study is applied for conventional wells. The emission factor provided in the EPA/GRI study is 2,454 Mcf of methane/workover. Minor adjustments to this emission factor are believed to be reflected in Table 2 to account for different methane compositions in each region. For unconventional well workovers, the TSD indicates that the emission factor is assumed to be the same as unconventional well completions. An analysis of the unconventional completion emission factor and emission estimates is provided in the following section.

As noted previously, EPA adjusts the total national inventory for emission reductions reported through the Gas STAR program and reductions that results from regulatory requirements, such as NESHAP. Hence, it is also not possible to determine which of the emission reductions shown in Table A-125 and A-126 are attributed unconventional well workovers, as the tables do not split reductions by activity.

1.3 Unconventional Well Completions

As a part of the 2009 inventory, “unconventional well completions” is added as a new emission source to the "Drilling and Well Completion" inventory category. Unconventional well completions now account for approximately 7% of the total natural gas production CH_4 emissions, where as in 2008, “well drilling” emissions accounted for approximately 0.07% of total natural gas production CH_4 emissions.

EPA’s inventory documentation does not reference the source of information for the reported counts of wells drilled and unconventional completions. The only statement is that “the

Inventory tracks activity data for unconventional well counts (which we assumed to be completed by hydraulic fracture for the purposes of this analysis) in each region." EPA should indicate which of the numerous references listed for activity data are associated with the individual emission sources, particularly if activity data are derived from other information.

The regional emission factors used for unconventional gas well completions are the same as those used for unconventional gas well workovers (shown in Table 2). The emission factors for unconventional gas well completions are much larger than the emission factors for well drilling; as noted for well workovers. EPA justifies the use of larger emission factors due to the higher pressure venting of gas used to drive large volumes of liquid from the production well.

As mentioned for unconventional well workovers, EPA does not describe how the emission factor for unconventional gas well completions was developed. For unconventional completions, the TSD associated with 40 CFR 98 Subpart W indicates the emission factor was derived from participant information shared and presented at Natural Gas STAR technology transfer workshops. EPA cites two Gas STAR presentations as the source of information for the unconventional well completion/workover emission factor[3]. The TSD for Subpart W provides further details on the data specifically used in developing the Subpart W average emission factor of 9,175 Mscf/completion. It is assumed that the emission factors shown in Table 2 vary from the Subpart W average emission factor due to different gas compositions in the region, but this is not documented in the inventory.

Table 3 summarizes the information presented in the two Gas STAR presentations referenced in the 2009 national inventory and demonstrates the basis for the average emission factor.

Table 3. Data Support EPA's Emission Factor for Unconventional Completions/Workovers

Data Source		# Wells	Gas Volumes	Uncontrolled Emission Factor, Mscf/well	Rounded Emission Factor, Mscf/well	Notes and Comments
"Green Completions", Lessons Learned from Natural Gas STAR, Producers Technology Transfer Workshop, September 21, 2004[4]	2002 EIA Data	7,783	44.7 Bcf	5,744	6,000	The EIA gas volumes represent combined vented and flared gas from completions
	Source not identified	No count provided	7 to 12,500 Mcf recovered (2-89% of total gas)	3,000	EPA did not use this data.	

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[3] EPA. Reducing Methane Emissions During Completion Operations. Natural Gas STAR Producer's Technology Transfer Workshop. September 11, 2007.
Available online at: <http://epa.gov/gasstar/documents/workshops/glenwood-2007/04_recs.pdf>.
EPA. Green Completions. Natural Gas STAR Producer's Technology Transfer Workshop. September 21, 2004.
Available online at: <http://epa.gov/gasstar/workshops/techtransfer/2004/houston-02.html>.

[4] http://www.epa.gov/gasstar/documents/workshops/houston-2004-2/GreenCompletions.ppt

Data Source		# Wells	Gas Volumes	Uncontrolled Emission Factor, Mscf/well	Rounded Emission Factor, Mscf/well	Notes and Comments
	BP	106	350 MMscf total gas recovered	3,669	EPA did not use this data.	Uncontrolled emission factor assumes 90% of the gas was recovered
	Devon	30	Total not provided	11,900	10,000	Gas volume represents recovered natural gas
	CBM wells	3	2.22 MMscf	741	700	
"Reducing Methane Emissions During Completion Operations", 2007 Natural Gas STAR Production Technology Transfer Workshop, September 11, 2007[5]	Williams, 2006	426	10.9 Bcf	25,500	20,000	Williams' presentation provides data that demonstrates the majority of this gas is recovered, and the small amount that is not recovered is either vented or flared (see Table 6)
	Williams, 2005	275	8.07 Bcf	29,345		
	Williams, 2004	241	5.06 Bcf	20,996		
	Williams, 2003	76	1.23 Bcf	16,145		
	Williams, 2002	46	0.79 Bcf	17,261		
					9,175	Straight Average

API notes the following based on reviewing the information in Table 3:

- EIA clearly indicates that the volumes reported are vented and flared emissions combined. EPA is assuming the total volume of gas is vented, which inflates the emission factor. It is also interesting that although EIA reports this information annually, EPA only evaluated the 2002 data presented in the Gas STAR report.
- EPA did not use the information provided by the second (unidentified) source. This data set shows a wide spread of recovered gas volumes and percentages. As this was presented at a Gas STAR workshop, it would be useful if EPA could request more details on this data from the source of the information.
- It is not clear why EPA did not include the information presented by BP. The BP data point represents a controlled completion and would support the development of a controlled emission factor.
- The Williams data provides the total amount of gas generated from completions. However, the Williams presentation provides data that demonstrates the majority of this gas is recovered, and the small amount that is not recovered is either vented or flared. **In fact, using the data Williams provides, which demonstrates the actual emissions that result accounting for emission reduction activities, produces an average emission factor of approximately 2,000 Mscf/well, which is about one-fifth of the emission factor used in EPA's inventory.**

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[5] http://www.epa.gov/gasstar/documents/workshops/glenwood-2007/04_recs.pdf

For this source it is not clear where EPA may adjust the emissions to account for emission reduction activities or regulatory requirements, such as flaring. EPA notes "*some states, such as Wyoming, may require that natural gas produced during well completions not be vented. In these regions emissions from natural gas well completions and re-completions are either recovered for sales or must be flared. The volume of gas recovered by bringing equipment to the wellsite for the treatment and injection of the produced completion gas into the sales pipeline is reported by Natural Gas STAR. The remaining volume of completion gas from states that do not allow the venting of this gas is flared*". The inventory includes a source "completion flaring" but EPA does not discuss how this source relates to the unconventional completion emissions.

The number of completions flared does not appear to have changed, and in fact is slightly larger for 2009 compared to 2008. This indicates that EPA has not made a significant adjustment to the accounting for emissions from completion flaring. However, it would seem that some portion of the unconventional completion emissions would be flared and should thus be represented in the source category for completion flaring. EPA should reflect the actual flared and vented emissions, as represented by current industry practices, by appropriately accounting for completion emissions that are vented versus flared and eliminating the artificial inflation of the emission factor and potential double counting of some completion activities.

1.4 Well Clean Ups (LP gas wells)

In the 2009 inventory, the total emissions from "well clean ups" account for approximately 51% of the total natural gas production sector CH_4 emissions. For comparison, in the 2008 inventory, well clean up emissions accounted for approximately 6% of the total natural gas production CH_4 emissions, when not accounting for emission reductions due to Natural Gas STAR or other regulations.

EPA notes that the methodology for quantifying emissions from this source category was revised to include a large sample of well and reservoir characteristics from the HPDI database of production and permit information along with an engineering equation to estimate the volume of natural gas necessary to expel a liquid column choking the well production. The approach used for the emission factor is based on a fluid equilibrium calculation to determine the volume of gas necessary to blow out a column of liquid for a given well pressure, depth, and casing diameter.

EPA notes in Section 3.6 that the HPDI database for well production and well properties was queried to obtain sample data on average well depth, shut-in pressure, well counts, and well production rates from each basin. Although EPA does not state explicitly, it is implied that differences in these characteristics across basins account for the regional differences reported in the inventory. For complete transparency, EPA should publish the equation and the average characteristics used for each basin.

Emission reductions for this source type are significant. EPA even notes that emission reductions may be under reported in the Planned Improvements portion of Section 3.6, and that the potential for emission reductions from gas well cleanups to be underestimated will be investigated in the next Inventory cycle. The Natural Gas STAR Lessons Learned for installing plunger lift systems reports emission reduction ranging from 4,700 to 18,250 Mscf/yr. In addition, the West Coast emission factor, the second largest of the regional factors, clearly does not account for the practices in California, where petroleum producers have strict emission controls on CH_4. EPA describes in Annex 3.4 that some states may require that natural gas produced during well completions not be vented; in these regions the natural gas is recovered to sales or flared. The natural gas from gas well clean ups can also be recovered to sales or flared. Alternatively, if gas and liquids/water are piped separately to the surface from a gas well, and any artificial lift method (not just plunger lift) was applied to bring the liquids to the surface, then there would be no venting of gas and liquids from the well from liquids unloading. All such artificial lift practices and other methods for reducing emissions should be clearly identified in EPA's inventory. The inventory should provide separate factors for controlled and uncontrolled activities, as is done for condensate tanks.

1.5 Flashing Losses from Oil and Condensate Tanks

The 2009 national inventory includes an adjustment to the condensate tank emission factors for the Mid-Central and South West regions for both condensate tanks without control devices and condensate tanks with control devices. EPA noted in Section 3.6 that the 2009 inventory includes, for the first time, data from a Texas Environmental Research Consortium (TERC) study (TERC 2009)[6] which provided a small sample of data representing two regions in Texas where separator dump valve malfunctions were detected and measured. The TERC study measured emissions rates from several oil and condensate tanks in Texas. These data were plotted and compared to flashing emissions simulated via E&P Tanks. EPA observed that the E&P Tanks results indicated additional emissions beyond flashing losses were present in approximately 50 percent of the tanks and concluded that the emissions may be attributed to separator dump valves malfunctioning or other methods of associated gas entering the tank and venting from the roof.

It is not clear how EPA applied the TERC study data to determine the 2009 emission factors. The TERC study specifically addressed Volatile Organic Compounds (VOC) emissions from oil and condensate storage tanks, and also provided vent sample data, including for methane. The TERC study was designed to specifically capture all of the emissions from each tank, and therefore it is unlikely that half of the tanks measured would have missed emissions. In addition, the TERC study did not capture all of the input data necessary to run E&P Tanks (e.g., pressurized separator liquid compositions). Therefore, it seems more likely that the "additional emissions" resulting from EPA's simulation runs of the flashing emissions are actually a result of assumptions EPA used to assign the model input parameters.

Furthermore, the E&P Tanks modeling EPA is referencing does not incorporate dump valve malfunctions as an emission parameter in the model algorithm. If EPA wishes to accurately quantity emissions from separator dump valve malfunctions, testing should be performed to specifically focus on emissions from malfunctioning dump valves.

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[6] TERC (2009). VOC Emissions from Oil and Condensate Storage Tanks. Hendler, Albert, URS Corporation; Nunn, Jim, COMM Engineering; Lundeen, Joe, Trimeric Corporation. Revised April 2, 2009. Available online at: <http://files.harc.edu/Projects/AirQuality/Projects/H051C/H051CFinalReport.pdf>.

The activity factors for condensate tanks did not vary significantly from 2008 to 2009. However, EPA does not clearly identify how the throughput is differentiated between tanks with and without control devices. Instead, it appears that the same throughput is being applied to each tank type, presumably based on an assumption that 50% of tanks are controlled. EPA should clearly identify what source was used to obtain the throughput information for each tank type.

1.6 Centrifugal Compressors

The 2009 inventory includes for the first time emission factors for centrifugal compressors by seal type (wet and dry seals, respectively) for the natural gas processing and natural gas transmission sectors. Table 4 compares the 2008 and 2009 emission factors and equipment counts by sector.

Table 4. Comparison of Centrifugal Compressor Emissions for 2008 and 2009

	2008 Inventory		**2009 Inventory**			
	Centrifugal Compressors		**Centrifugal Compressors – Wet Seals**		**Centrifugal Compressors – Dry Seals**	
Sector	**Emission Factor (scfd/ compressor)**	**Number of Compressors**	**Emission Factor (scfd/ compressor)**	**Number of Compressors**	**Emission Factor (scfd/ compressor)**	**Number of Compressors**
Natural Gas Processing	21,230	771	51,370	646	25,189	140
Transmission	30,305	705	50,222	667	32,208	55
Storage	30,573	116	45,441	84	31,989	29

As shown in Table 4, the emission factors for centrifugal compressors increased from 2008 to 2009, regardless of seal type. The resultant emissions increase was most significant in the gas processing sector. Table 4 also shows that the activity factors for compressors have been split into compressors with wet and dry seals. However, EPA does not clearly identify how the counts of compressors were allocated between wet and dry seals or what information source EPA used to make this allocation. An EPA Natural Gas STAR Lessons Learned paper on replacing wet seals with dry seals[7] notes that about 90 percent of all new compressors come with dry seals. It is anticipated that the number of centrifugal compressors with wet seals will decrease over time as centrifugal compressors with wet seals are replaced by centrifugal compressors with dry seals.

EPA notes that the centrifugal compressor emission factors were revised as a part of the 2009 inventory based on guidance from a World Gas Conference paper (WGC, 2009), which gathered 48 sample measurements of centrifugal compressor wet seal oil degassing emissions and published the results. The World Gas Conference paper, which is cited as the source of the 2009 inventory emission factors, is actually in turn citing a combination of data provided in the

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[7] EPA (2006b) Replacing Wet Seals with Dry Seals in Centrifugal Compressors. Lessons Learned from Natural Gas STAR Partners. October 2006. <http://epa.gov/gasstar/documents/ll_wetseals.pdf>.

Natural Gas STAR paper on replacing wet seals with dry seals[8] and a Methane to Markets study of measurements at four gas processing plants[9]. The WGC report notes that

> "*Methane to Markets experience, combined with another assessment of four natural gas facilities, has identified measurements from 48 wet seal centrifugal compressors, with methane emissions totaling 14,860 thousand m^3 methane/year. The data, which show that seal oil degassing rates for individual compressors could range from 0 to 2,756 thousand m^3/year, can be divided into two groups: a low-emitting group (33 compressors) and a high-emitting group (15 compressors). The low emitters have an average emission rate of 26 thousand m^3 methane/year for a single compressor. The high emitters have an average emission rate of 934 thousand m^3 methane/year for a single compressor.*"

The basis of the EPA wet seal emission factors is not clear and is inconsistent with Subpart W of the EPA's Mandatory Reporting Rule. Subpart W, §98.233(o)(7), presents a default wet seal compressor emission factor of 12.2 million scf methane/yr (at 68°F and 14.7 psia), which converts to 33,425 scfd/compressor – consistent with the data presented in the WGC report. The values used for the 2009 EPA inventory are much higher, at 51,370 scfd/compressor for processing, 50,222 scfd/compressor for transmission, and 45,441 scfd/compressor for storage. EPA does not provide documentation to explain the basis for the differences among the industry sectors. The Subpart W default emission factor for wet seal compressor degassing is based on 14,860 thousand m^3 methane/yr from the World Gas Conference paper divided by 43 centrifugal compressors (EPA Technical Support Document, 2010). Note that denominator is 43 compressors rather than all 48. The Technical Support Document indicates that five of the 48 wet seal centrifugal compressors were found to not be emitting[10]; thus the emission factor is incorrectly averaged only over the leaking compressors and does not account for the fact that a portion of the compressor seals do not leak, thus the total number of compressors (i.e. 48) ought to be included when deriving the emission factor.

Table 5 of the Methane to Markets paper presents a comparison of the emission factors measured during the study to the EPA/GRI 1996 emission factors. The average factor measured for compressor seals was 0.852 kg THC/h/source, while the EPA/GRI (1996) study average factor was actually larger by about 30%, at 1.172 kg THC/h/source. Footnote 4 to Table 5 notes that the "*compressor seals component category accounts for emissions from individual compressor seals. As compressor seal leakage was typically measured from common vent and drain lines, emissions have been divided evenly among the seals on units with detected leakage*." The factors are not split by wet or dry seals. As Appendices I and II (containing site specific field measurement data) are missing to protect business confidentiality, it is not possible to determine whether the study further separates compressor seal measurements into wet and dry seals.

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[8] EPA (2006b) Replacing Wet Seals with Dry Seals in Centrifugal Compressors. Lessons Learned from Natural Gas STAR Partners. October 2006. <http://epa.gov/gasstar/documents/ll_wetseals.pdf>.

[9] EPA/GTI/Clearstone. Identification and Evaluation of Opportunities to Reduce Methane Losses at Four Gas Processing Plants. June 20, 2002. <http://epa.gov/gasstar/documents/four_plants.pdf>.

[10] EPA (2010) Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry, Background Technical Support Document. 2010. <http://www.epa.gov/climatechange/emissions/downloads10/Subpart-W_TSD.pdf>.

EPA does not directly cite a source for the updated dry seal emission factors, but provides in the References section for the Natural Gas Systems a reference to the Natural Gas STAR paper discussed above. The executive summary of the paper notes that dry seals emit up to 6 scfm; on page 4 of the paper it is noted that dry seals emit less during normal operation (0.5 to 3 scfm across each seal, depending on the size of the seal and operating pressure). The cost savings in Exhibit 5 are calculated assuming 2 dry seals at a total of 6 scfm.

If EPA is citing the Natural Gas STAR paper as the reference for the dry seal emission factor, it can be assumed that the emission factor derived from such data will be on an order of magnitude similar to that provided in the reference document. It can conservatively be assumed that the emissions will be estimated using the maximum leakage rate (6 scfm), instead of the normal operation leakage rate (0.5 to 3 scfm). However, when converting the 6 scfm identified in the Natural Gas STAR paper to a scfd basis, as is used in the 2009 inventory, the factor should be around 8,640 scfd/compressor on a natural gas basis, even lower on a methane basis, and significantly less than the factor shown in the 2009 inventory for natural gas processing (25,189 scfd/compressors), transmission (32,208 scfd/compressors), and storage (31,989 scfd/compressors). EPA should explain these differences and clearly state the reference of the emission factors for each segment.

2. Additional Comments on the Revised National Inventory

2.1 National Energy Modeling System (NEMS) Regions

EPA notes that the regions are divided in accordance with the National Energy Modeling System. However, according to EIA[11], the NEMS regions are: Pacific, Mountain, West North Central, East North Central, New England, Middle Atlantic, South Atlantic, East South Central, and West South Central. EPA should clearly identify which of the NEMS regions are included in each of the natural gas production regions (North East, Mid-Central, Rocky Mountain, South West, West Coast, and Gulf Coast).

In addition, Texas (the state for which the TERC study was conducted) falls into one NEMS region: West South Central. Yet in the 2009 inventory, the condensate storage tank emission factors for both the Mid-Central and South West regions were revised. EPA notes in Section 3.6 that because the TERC dataset was limited to represent production from only 14 counties that represent 0.5 percent of U.S. production, the national emission factor was scaled up such that only production from these counties is affected by the occurrence of associated gas venting through the storage tank. EPA should clearly identify how the factors for both the Mid-Central and South West regions were adjusted. If Texas does fall within both the Mid-Central and South West regions, and if the factors were truly scaled according to the counties affected, the factors should not be identical for both Mid-Central and South West regions.

2.2 Updated API Compendium

API provided comment on the draft 1990 – 2008 inventory that, as indicated above, API revised the API Compendium in 2009. References to emission factors from the API Compendium

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[11] EIA. The National Energy Modeling System: An Overview 2009. <http://www.eia.doe.gov/oiaf/aeo/overview/figure_1.html>

should be updated to reflect the 2009 version of API's *Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry*. For example, Section 3.7 Petroleum Systems (p. 3-51, line 15) and Annex 3.5 Petroleum Systems (p. A-168, line 34) reference "API (2004)", but should instead reference the newest version of the API Compendium as the source of the asphalt blowing emission factor.

2.3 Asphalt Blowing

API provided comment on the draft 1990 – 2008 inventory that the most significant change noted in the 2008 national inventory was the addition of asphalt blowing CO_2 emissions for refineries in the Petroleum Systems category. This emission source accounted for 36% of the total non-combustion CO_2 emissions from petroleum systems in 2008, and accounts for 31% of the total non-combustion CO_2 emissions from petroleum systems in 2009.

The CH_4 factor for asphalt blowing in the 2009 EPA *Inventory of Greenhouse Gas Emissions and Sinks* is the same as is used in the 2008 EPA *Inventory of Greenhouse Gas Emissions and Sinks*. As a part of API's comments on the draft 1990 – 2008 inventory, API also noted that neither emission factor is consistent with the 2009 API Compendium. The 2009 Compendium presents the same factor as the 2004 API Compendium, which is the cited source of the emission factor used in the EPA *Inventory of Greenhouse Gas Emissions and Sinks*.

The 2009 API Compendium cites a simple emission factor for uncontrolled asphalt blowing from AP-42 (EPA, AP-42, Section 5.1.2.10, 1995). The AP-42 emission factor for asphalt blowing is assumed to be on an air-free basis (AP-42 does not specify this, but notes the factor represents "emissions"). Asphalt blowing exhaust composition data (13 mol% CH_4 and 9 mol% CO_2, on an air free basis) presented in an Oil & Gas Journal article[12] is applied to derive the CH_4 and CO_2 emission factors of 5.55E-4 tonnes CH_4/bbl asphalt blown and 1.01E-3 tonnes CO_2/bbl asphalt blown, respectively. (Further details on the derivation of these emission factors are provided in Appendix B of the 2009 API Compendium.)

For comparison, the EPA emission factors converted to a similar basis are 4.9E-5 tonnes CH_4/bbl and 1.09E-3 tonnes CO_2/bbl. However, the primary distinction between the API Compendium emission factors and those used in the EPA inventory is the units of measure applied to the activity factor. The API emission factors are based on the volume (or mass) of asphalt blown, while the EPA emission factors appear to be based on the total volume of asphalt produced (411 Mbbl/cd production). As a result, the EPA emission factors result in much higher emission estimates.

2.3 Refining Emissions

There are a number of sources that do not appear to be included in the national GHG inventory. For the refining sector, these include CO_2 emissions from flares, hydrogen production, catalytic cracking units, fluid coking units, catalytic reforming units, sulfur recovery units, and coke calcining units. Emissions from each of these sources are required to be reported under the

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[12] Dimpfl, L.H. Study Gives Insight Into Asphalt Tank Explosions, "Oil and Gas Journal", December 1980

GHGRP, and for which EPA had to assess the emissions as part of the justification for their inclusion in the regulation. The inventory should incorporate EPA's current understanding of these emissions or document why they are excluded from the inventory.

2.4 Alignment with the EPA GHG Reporting Program

EPA indicates in the Planned Improvements portion of both of Sections 3.6 (Natural Gas Systems) and 3.7 (Petroleum Systems) that data collected through 40 CFR Part 98 (Mandatory Reporting of Greenhouse Gases; Final Rule) will be used as a source for potential improvements to the inventory. API supports the continued improvement of the national inventory, but urges EPA to provide transparent justification and formal technical review for the changes.

In Section 3.6 (page 3-48, line 25) EPA notes that reporting will begin in 2010 for natural gas suppliers. EPA is referring to reporting under Subpart NN (Suppliers of Natural Gas and Natural Gas Liquids) for local distribution systems. However, Subpart NN only requires reporting of volumes and emissions associated with potential end-use combustion of the natural gas and the natural gas liquids supplied. The information reported under Subpart NN does not represent actual emissions, and if the gas supplied were to be combusted their emissions would fall under Section 3.1 (Fossil Fuel Combustion), not to Section 3.6.[13]

EPA should clarify that data collection begins for Subpart NN in 2010, with emissions reported beginning in 2011 for calendar year 2010. In addition, if EPA is implying that emissions reported under Subpart W will be used to improve the Natural Gas Systems inventory, EPA should clarify that data collection for Subpart W begins in 2011, with emission reporting beginning in 2012 for calendar year 2011.

In Section 3.7 (page 3-52, line 37) EPA notes that U.S. petroleum refineries will be required to calculate and report their greenhouse gas emissions beginning in 2010. EPA should clarify that data collection begins for petroleum refineries in 2010, with emissions reported beginning in 2011 for calendar year 2010.

3. Recommendations

1. (Section 3.6 and Annex 3.4, Natural Gas Systems) The changes to the emission factors for gas well workovers, gas well cleanups, well completions, condensate storage tanks, and centrifugal compressors should all be documented in Section 3.6 and Annex 3.4, as discussed above. Many other emission factors also changed from 2008 to 2009; a few examples are provided in Table 5. One example is provided for each region except West Coast, for which the emission factor revisions are due to rounding differences between the two inventories. Note that the table below is not all inclusive of the emission factor revisions. The reasons for all emission factor revisions should be documented in the inventory, not just the reasons for major emission factor revisions.

---

[13] Interestingly, in Section 3.7 Petroleum Systems (page 3-50, line 14), EPA notes that "the estimates of CH_4 emissions from petroleum systems do not include emissions downstream of oil refineries because these emissions are <u>negligible</u>."

Table 5. Examples of 2008 to 2009 Emission Factor Revisions

Activity	Region	Emission Factor 2008	Emission Factor 2009
Small Reciprocating Compressors	North East	269 scfd/comp	284.95 scfd/comp
Large Reciprocating Compressors	Mid-Central	16,013 scfd/comp	16,135 scfd/comp
Normal Operations – Dehydrator Vents	Rocky Mountain	274.3 scf/MMscf	275 scf/MMscf
SW – Unconventional Gas Wells	South West	NA	36.52 scfd/well
Large Reciprocating Stations	Gulf Coast	9,266 scfd/station	9,270.90 scfd/station

2. (Annex 3.4 Natural Gas Systems) Emission factors and activity factors are only provided for 2008 (with the exception of “key activity data drivers” provided in Table A-124), yet emissions are shown for multiple years. API recommends adding emission and activity factors for all years for which emissions are being estimated, for full disclosure. (In addition, it is discussed in Step 1 that activity factors vary by year.)

3. (Annex 3.4 Natural Gas Systems) If emission factors determined for 1995 are assumed to be representative of emissions from each source type over the period 1990 through 2009, API recommends adding that information to Step 1 or Step 3, similar to the text in Annex 3.5 Petroleum Systems, p. A-168, line 21. Alternatively, if emission factors are not assumed to be representative of emissions from each source type over the period 1990 through 2009, this should be noted as well, and emission factors should be added for all years for which emissions are being estimated, for full disclosure.

4. (Annex 3.5 Petroleum Systems) Emission factors and activity factors are only provided for 2009, yet emissions are shown for multiple years. API recommends adding emission and activity factors for all years for which emissions are being estimated, for full disclosure. (In addition, it is discussed in Step 2 that activity factors vary by year.)

4. Editorial Comments

- (Section 3.7 Petroleum Systems, Tables 3-43, 3-46, and 3-47) API recommends adding a note that indicates “Totals may not sum due to independent rounding.”
- (Section 3.7 Petroleum Systems, Tables 3-43) The values shown for Tank Venting for 2005, 2006, and 2008 should be 0.2 Tg CO_2 Eq., not 0.3 Tg CO_2 Eq. This change corresponds with the values shown in Table A-142 for Tank Venting. API recommends verifying the values.
- (Section 3.7 Petroleum Systems, Table 3-47) The totals shown appear to vary more than would be due to rounding error. For example, the 2008 total should be approximately 43,410 Gg, but is shown as 43,311 Gg. API recommends verifying the totals.
- (Section 3.7 Petroleum Systems, Tables 3-43 and 3-46) Where tables are split onto multiple pages, EPA should add the table header for each continued page.

- (Annex 3.4 Natural Gas Systems, and Annex 3.5 Petroleum Systems) Multiple table references have a space before the table number. Tables are currently referenced as "Table A- X" and should be "Table A-X".
- (Annex 3.4 Natural Gas Systems, p. A-150, Step 1, Second Paragraph, Line 3) The reference to "Table A-123" should instead be to "Table A-124".
- (Annex 3.4 Natural Gas Systems, Multiple Tables) Where tables are split onto multiple pages, EPA should add table header for each continued page.
- (Annex 3.4 Natural Gas Systems, Table A-123) Emission factor units for Mishaps (Dig-ins) should be "Mscfy/mile" instead of "mscfy/mile", to be consistent with the other units presented in the annex.
- (Annex 3.4 Natural Gas Systems, Table A-125) API recommends adding a note that indicates "Totals may not sum due to independent rounding."
- (Annex 3.5 Petroleum Systems, Tables A-136 through A-138, and Table A-141) API recommends adding a header row above the last four columns noting "2009 EPA Inventory Values", similar to the table presentation for Annex 3.4 (Natural Gas Systems).
- (Annex 3.5 Petroleum Systems, p. A-170, Table A-137) Remove the period after "bbl" in the units for the emission factor and activity factor for Heaters.
- (Annex 3.5 Petroleum Systems, p. A-170, Table A-138, and p. A-172, Table A-141) API recommends spelling out "cd" for emission factors with units of "cd refinery feed" or "cd feed".
- (Annex 3.5 Petroleum Systems, p. A-170, Table A-137) API recommends formatting with the Activity Factor for the Marine Loading and Pump Stations activity factors. The Marine Loading activity factor appears to have a digit (4) on the row below; the Pump Station activity factor does not clearly show all digits.
- (Annex 3.5 Petroleum Systems, p. A-169) API recommends mentioning Table A-140, and how the values presented are used in calculation of the CO_2 emissions presented in Annex 3.5.
- (Annex 3.5 Petroleum Systems, p. A-171, Table A-139) API recommends adding a note that indicates "Totals may not sum due to independent rounding."
- (Annex 3.5 Petroleum Systems, p. A-172, Table A-142) The value shown for Production Field Operations should be 317 instead of 319, which affects the total row in Table A-142 (the total should be 461 Gg instead of 463 Gg) and the values shown in Table 3-43 and Table 3-44.

Sincerely,

Karin Ritter

Attachment B

Attachment B

WERF
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Collaboration. Innovation. Results.

Greenhouse Nitrogen Emission from Wastewater Treatment Operations

INTERIM REPORT

Attachment B

U4R07a

GREENHOUSE NITROGEN EMISSION FROM WASTEWATER TREATMENT OPERATIONS

INTERIM REPORT

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2010

WERF

The Water Environment Research Foundation, a not-for-profit organization, funds and manages water quality research for its subscribers through a diverse public-private partnership between municipal utilities, corporations, academia, industry, and the federal government. WERF subscribers include municipal and regional water and wastewater utilities, industrial corporations, environmental engineering firms, and others that share a commitment to cost-effective water quality solutions. WERF is dedicated to advancing science and technology addressing water quality issues as they impact water resources, the atmosphere, the lands, and quality of life.

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LIST OF ACRONYMS

ASM	Activated Sludge Model	TKN	Total Kjeldahl nitrogen
BNR	Biological Nutrient Removal	U.S EPA	U.S. Environmental Protection Agency
BOD	Biochemical Oxygen Demand	WERF	Water Environment Research Foundation
COD	Chemical Oxygen Demand	IPCC	Intergovernmental Panel on Climate Change
DO	Dissolved oxygen	WWTP	Wastewater Treatment Plants
N_2O	Nitrous oxide	Nir	Nitrite Reductase
NO	Nitric oxide	Nor	Nitric oxide Reductase
GHG	Greenhouse gas	NaR	Nitrate Reductase
GWRC	Global Water Research Coalition	N_2OR	Nitrous oxide Reducatase
mg/L	Milligrams per Litre	SCAQMD	South Coast Air Quality Management District
mgd	Million-Gallons per Day	AOB	Ammonia-oxidizing Bacteria
SRT	Solids Retention Time	N_2O_4	Dimeric nitrogen dioxide
NH_4^+	Ammonium	SEIFC	Surface emission isolation flux chamber
NH_2OH	Hydroxylamine	GC	Gas Chromatograph
O_3	Ozone	TCD	Thermal Conductivity Detector
nm	Nanometer	IR	Infra-red
sCOD	Soluble Chemical Oxygen Demand	FTIR	Fourier Transform Infrared Spectroscopy
ATCC	American Type Culture Collection	AMO	Ammonia monooxygenase
PCR	Polymerase Chain Reaction	HAO	Hydroxylamine oxidoreductase
sOUR	Specific Oxygen Uptake Rate	NIOSH	National Institute for Occupational Safety and Health
DNA	Deoxyribonucleic acid	ORP	Oxidation Reduction Potential
Da	Dalton	MLE	Modified Lutzack Ettinger
SBR	Sequencing Batch Reactor	rbCO	readily biodegradable COD
HRT	Hydraulic Retention Time	ffCOD	filtered-flocculated chemical oxygen demand
ppmv	Parts Per Million by Volume	RNA	Ribonucleic acid
sDNR	Specific Denitrification Rates	mRNA	messenger RNA
UQ	Ubiquinone	rRNA	Ribosomal RNA
N_2	Nitrogen gas	Cyt	Oxidase Cytochrome Oxidase

EXECUTIVE SUMMARY

Problem Definition

The push to achieve greater nutrient removal from wastewater treatment plant effluents has resulted in the development of a wide range of innovative biological nitrogen removal (BNR) processes. However, BNR strategies could be a potential contributor to atmospheric N_2O and NO depending upon the reactor configurations and operating conditions. In the future, as BNR is implemented at wastewater treatment plants nationwide, the flux of these gases to the atmosphere could increase. Such increased releases would be of possible concern since the greenhouse impact of nitrous oxide is about three hundred times that of carbon dioxide.

Project Description

The goal of this project is to characterize nitrogenous emissions from the activated sludge portion (only) of wastewater treatment plants. This project represents one of the first attempts at characterizing nitrogenous GHG emissions from wastewater treatment plants, and at developing a methodology for collection of full scale plant data from a range of nutrient removal facilities in the United States. Building on previous work by the project team, this information will be integrated into a mechanistic activated sludge process model, which will be refined through this project by the addition of autotrophic pathways for N_2O and NO emission. The refined mechanistic model will allow the industry to codify the results of this research, and develop a tool that will aid in the prediction and therefore, mitigation of N_2O, NO, and NO_2 emissions from WWTPs utilizing a range of wastewater treatment processes. Ultimately, this would allow the wastewater sector to engineer strategies for wastewater treatment that minimize gaseous nitrogen oxide emissions.

This study is the first of its kind in the United States and there are only two other similar studies being conducted in the Netherlands and Australia. To facilitate a global monitoring effort, the protocol developed in this study has been shared upon request with additional groups in Spain, Portugal, Germany and Belgium, which are just beginning similar monitoring programs. It is expected that broad application of the protocol will allow WWTPs to quantify their N_2O emissions using a standard approach and to ultimately engineer environmentally sustainable BNR operating strategies and configurations.

Project Objectives

The objectives of this project were to:

- Identify principal aqueous and gaseous intermediates in activated sludge tanks under different configurations, nitrogen loads, and operating conditions (i.e. extant dissolved oxygen concentrations).
- Determine the relative mechanisms and contributions of oxidative and reductive pathways in gaseous nitrogen oxide production by activated sludge bacteria.
- Develop a tool based on activated sludge model (ASM) algorithms augmented to allow the results of this research to be codified and available for use. The tool will facilitate optimization of nutrient removal processes to minimize both aqueous and gaseous nitrogen greenhouse gas (GHG) emissions. This step is not part of this interim study report.
- Conduct a full-scale demonstration study aimed at mitigation of N_2O emissions at a selected BNR activated sludge facility. This step is ongoing and also not included in this interim report.

These project objectives have been accomplished via two inter-related components: characterization of nitrogen greenhouse gas emissions from full scale wastewater treatment operations (nitrification/denitrification process tanks) and bench-scale reactors experiments conducted at Columbia University.

Project Results and Findings

National-Scale N_2O Measurement Survey: A wide range of N_2O emissions was measured across the twelve WWTPs around the United States. For the twelve plants included in this analysis, on average, the fraction of influent TKN emitted as N_2O (mass/mass) was in the range 0.01-1.8%. Measured emission factors (g-N_{2O}/population equivalent flow-year) were in the range 0.28-140. Emissions from aerobic zones were consistently higher than those from anoxic zones. Based on a multivariate linear regression model, ammonia, DO and nitrite concentrations correlate positively with N_2O emissions fluxes from aerobic zones. In anoxic zones, DO and nitrite correlate positively with N_2O emissions fluxes. Significant temporal variability was also observed in N_2O emissions with liquid-phase N-species concentrations correlating well with N_2O headspace concentrations. Based on these observations, a single lumped emission factor approach to 'estimating' N_2O emissions from wastewater treatment processes is not appropriate. Furthermore, due to significant differences in local or global wastewater composition (Tchobanoglous et al., 2003), the use of flow normalized emission factors to describe N_2O emissions is not recommended. Although not the primary focus of this study, emissions of nitric oxide (NO) were also concurrently measured during each sampling campaign. NO emissions were consistently far lower than N_2O emissions by at least a factor of 10-100. However, the *trends* in the concentration profiles of N_2O and NO were nearly identical. This parallel is consistent with the sequential formation of NO and N_2O by both nitrification and denitrification pathways.

Molecular Mechanisms of N_2O and NO Emissions from Nitrification: Based on lab-scale studies, the mechanisms of autotrophic (from nitrification) N_2O emissions were determined at the whole-cell and gene expression levels by subjecting chemostat cultures of *Nitrosomonas europaea* 19718 to transient anoxia. Contrary to the governing hypotheses, researchers found that N_2O production via nitrification is related to a *recovery* from anoxic conditions rather than *imposition* thereof. Additionally, in contrast to N_2O generation by denitrifying bacteria, the generation of NO and N_2O were mutually exclusive. N_2O generation occurred only during aerobic conditions whereas NO generation occurred only during anoxic conditions. The extent of N_2O emissions was also linked to ammonia concentrations in the nitrifying bioreactor. The production of NO and N_2O was attributed to a major imbalance at the gene expression level. Finally, a new dimensionless number that captures the ratio of the specific substrate utilization rate to the maximum substrate utilization rate, was formulated and used to describe the propensity of nitrifying bacteria for N_2O production.

Factors Impacting N_2O and NO Emissions from Denitrification: Lab-scale studies were also conducted to determine the factors for N_2O from denitrifying reactors operated using methanol and ethanol as external carbon sources. During steady-state operation, emissions of both N_2O and NO from either reactor were minimal and in the range of <0.2% of influent nitrate-N load. Subsequently, the two reactors were challenged with transient organic carbon limitation and nitrite pulses, both of which had little impact on N_2O or NO emissions for either electron donor. In contrast, transient exposure to oxygen led to increased production of N_2O (up to 7.1% of influent nitrate-N load) from ethanol grown cultures, owing to their higher kinetics and potentially lower susceptibility to oxygen inhibition. A similar increase in N_2O production was not observed from methanol grown cultures. These results suggest that for dissolved oxygen, but not for carbon limitation or nitrite exposure, N_2O emissions from heterotrophic denitrification reactors can vary as a function of the electron donor used.

CHAPTER 1.0

LITERATURE AND INTRODUCTION

1.1 Background

Based on recent field-scale measurements, engineered BNR facilities, while effective to varying degrees in reducing *aqueous* nitrogen pollution, could emit up to 7% of the influent nitrogen load as *gaseous* N_2O and NO (Kampschreur et al., 2008b). Such emissions are deleterious to the environment. The greenhouse equivalence of N_2O is about three hundred times that of carbon dioxide and both N_2O and NO contribute to depletion of the ozone layer (Ravishankara et al., 2009).

Although, from a fundamental perspective, N_2O and NO are known intermediates in heterotrophic denitrification (Knowles, 1982; Zumft, 1997) and autotrophic nitrification and denitrification (Anderson and Levine, 1986; Anderson et al., 1993; Kester et al., 1997; Ritchie and Nicholas, 1972; Stuven et al., 1992), the net contribution of BNR processes to N_2O emissions from wastewater treatment has only recently been explicitly acknowledged (U.S. EPA, 2009). Based on the latest U.S. EPA report on sources and sinks of N_2O from wastewater treatment operations, denitrification in anoxic zones is implicated as the dominant source of N_2O from BNR activated sludge reactors (U.S. EPA, 2009). However, nitrification could also play a role in N_2O generation and emission from WWTPs, especially under cycling between anoxic and aerobic conditions (Kampschreur et al., 2008b), as is common in BNR reactors. Therefore, N_2O fluxes from aerobic zones of WWTPs also need to be included in N_2O emissions inventories.

At this point, while there is considerable debate and interest on the ‘potential’ of constituent BNR processes for N_2O generation and emission, there are few reports that systematically quantify such emissions from full-scale BNR operations (Czepiel et al., 1995; Kampschreur et al.; 2008b, Kimochi et al.; 1998, Sommer et al., 1998; Sümer et al., 1995; Wicht and Beier, 1995). Of these, only one has been conducted in the United States and focuses on a single non-BNR WWTP in New Hampshire (Czepiel et al., 1995). Other full-scale studies have been conducted in Europe and have employed different methods for measuring N_2O emissions including the use of grab samples (Czepiel et al., 1995; Kampschreur et al.; 2008b, Sommer et al., 1998; Sümer et al., 1995; Wicht and Beier, 1995) or online measurements (Kampschreur et al., 2008b; Kimochi et al., 1998). Given the broad diversity of BNR and non-BNR configurations that exist in the United States, a more detailed N_2O emissions database of WWTPs was needed, specifically obtained using a consistent protocol. Despite recognition of the possible role of biological nitrogen removal (BNR) processes in nitrous oxide (N_2O) emission, a measured database of N_2O emissions from these processes at the national scale does not currently exist. This project focused on the quantification of N_2O emissions at twelve wastewater treatment plants (WWTPs) across the United States using a newly developed U.S. EPA reviewed protocol. A subsequent focus was on determining the mechanisms and triggers of these emissions.

The principal motivation of conducting such a detailed monitoring campaign is the limited data currently used to "estimate" the N_2O emissions of WWTPs. The current method is based on emission factor values of 3.2 g N_2O/population equivalents/year from non-BNR operations and 7.0 g N_2O/population equivalent/year for BNR operations (Czepiel et al., 1995; U.S. EPA, 2009). Both emission factors are based on a limited data set and may not be broadly representative.

The release of N_2O from wastewater treatment processes is well recognized (U.S. EPA, 2009). The greenhouse impact of N_2O is about three hundred times that of carbon dioxide, the primary greenhouse gas (GHG). Furthermore, as recently shown, atmospheric N_2O can also contribute directly to the depletion of the atmospheric ozone layer (Ravishankara et al., 2009). From a regulatory and policy perspective, organizations such as the U.S. EPA are now beginning to explicitly include the contribution of BNR processes such as denitrification on the overall N_2O emission inventory from WWTPs (U.S. EPA, 2009). A common approach to estimating the N_2O inventory of wastewater treatment processes is by using a 'single' emission factor with a value of 3.2 g N_2O/population equivalent/year and 7.0 g N_2O/population equivalent/year for non-BNR and BNR processes (U.S. EPA, 2009). In these calculations, one population equivalent is defined as 100 gallons of wastewater discharged per capita per day. Conceptually, given that the inputs to a wastewater treatment plant and correspondingly the activity of the activated sludge bacteria are highly variable (Grady et al., 1999), it can be expected that there would be some degree of diurnal variability in N_2O emissions. Furthermore, owing to the fact that activated sludge bacteria have varying activities in different zones of the bioreactors (Grady et al., 1999), a certain degree of spatial variability in N_2O emissions is also expected from anoxic, anaerobic and even aerobic zones.

However, such spatial and diurnal variability in N_2O emissions is not considered in the simple emission factor approach adopted by the U.S. EPA and IPCC for estimating the N_2O

inventory of BNR and non BNR processes. Furthermore, by approximating the N_2O emissions from wastewater treatment processes using single emission factors across the board, the ability of certain operating conditions to selectively promote or minimize N_2O emissions is not understood. Furthermore, not all emission factors are created equal.

Based on these gaps in knowledge, the overall goal of the first part of this study (insert chapter number) was to quantify the emission of N_2O from WWTPs across the nation operated under different process conditions and configurations. The specific objectives of this first part of the study were to:

- Develop a database of N_2O emissions fluxes from different activated sludge process configurations using a standard protocol.
- Identify key factors that are correlated with N_2O emission from activated sludge.
- Determine the spatial and temporal variability in N_2O emissions from WWTPs (both BNR and non BNR) across the nation and examine the validity of the single emission factor approach in estimating the inventory of N_2O from WWTPs.

The remaining parts of this study deal with laboratory studies in pure and mixed cultures, modeling, and full scale demonstration of mitigation efforts via process engineering.

1.2 Mechanisms of Autotrophic N_2O and NO Emissions

There is now ample evidence of direct N_2O and NO generation by autotrophic ammonia oxidizing bacteria (AOB) under oxygen limitation or complete anoxia (Bock, 1995; Hooper et al., 1997; Schmidt and Bock, 1997; Schmidt and Bock, 1998). Under oxygen limiting and anoxic conditions, AOB including *Nitrosomonas europaea* and *N. eutropha* can utilize alternate electron acceptors such as nitrite (NO_2^-) or dimeric nitrogen dioxide (N_2O_4), and ammonium (NH_4^+) or hydrogen gas (H_2) as electron donors to produce substantial amounts of N_2O and NO. *N. europaea* indeed contains *nirK* and *norQB* gene homologs that encode a periplasmic copper-containing nitrite reductase (NirK) and nitric oxide reductase (Nor), respectively (Chain et al., 2003). Functional NirK and NorR enzymes have been detected during aerobic NH_4^+ oxidation in *N. europaea* (Beaumont et al., 2002; Beaumont et al., 2004a). NirK activity is essential to confer tolerance to nitrite in *N. europaea* and can result in NO production (Beaumont et al., 2002). There is some controversy about the exclusive production of N_2O and NO via nitrifier denitrification, as alternate paths for their production, including hydroxylamine (NH_2OH) chemodenitrification and auto-oxidation, may exist (Arp and Stein, 2003; Beaumont et al., 2002; Schmidt et al., 2004). Although it was thought that low oxygen tension is the primary factor contributing to NO and N_2O production (Colliver and Stephenson, 2000, Poth, 1985, Poth and Focht, 1985), production of N_2O has been described in *N. europaea* cultures under aerobic conditions (Beaumont et al., 2004a; Beaumont et al., 2004b; Shaw et al., 2006; Anderson and Levine, 1986).

Previous work on N_2O and NO generation by AOB in pure and mixed culture has shown that especially dynamic conditions (changes in oxygen or ammonium concentrations) lead to production of these gaseous compounds (Kampschreur et al., 2008a; Kampschreur et al., 2008b; Kester et al., 1997). However, the experimental designs of these studies do not allow discrimination of whether the generation of these gases is related to the *imposition* of anoxia or to *recovery* back to aerobic conditions and metabolic reactions after the anoxic shock (Kester et al., 1997). Furthermore, it is not a simple matter to predict the specific contribution of autotrophic and heterotrophic pathways to the overall N_2O and NO generation emission, which have been reported in some past mixed culture studies (Kampschreur et al., 2008a; Kampschreur et al., 2008b). Finally, from a fundamental perspective, the molecular underpinnings of N_2O and NO emissions from AOB in terms of functional gene expression are also largely unknown.

Based on experimental data from previous studies using AOB (Bock, 1995; Hooper et al., 1997; Ritchie and Nicholas, 1972; Schmidt and Bock, 1997) and known gene regulation in heterotrophic denitrifying bacteria (Zumft, 1997), it was hypothesized that transition from aerobic to anoxic conditions would stimulate the combined expression of nitrite and nitric oxide reductase genes in *N. europaea* and concurrently give rise to gaseous NO and N_2O. By corollary it was also hypothesized that upon *recovery* back to aerobic conditions, the gene expression and gaseous emission patterns would be suppressed, thereby leading to a reduction in NO and N_2O concentrations. The principal goal of this pure-culture component of the overall study was therefore to systematically determine the impact of transient anoxic conditions under different influent NH_4^+ concentrations on chemostat cultures of *N. europaea*.

1.3 Impact of Different External Carbon Sources on N_2O Emissions from Denitrification

Chemo-organo-heterotrophic denitrification is the dissimilatory reduction of ionic nitrogen oxides such as nitrate and nitrite, to nitric oxide (NO), nitrous oxide (N_2O) and ultimately to dinitrogen gas (N_2) using organic electron donors (Knowles, 1982). Sequential actions of several enzymes including nitrate reductase (NaR), nitrite reductase (NiR), nitric oxide reductase (NOR) and nitrous oxide reductase (N_2OR) are involved. As one of the two main reactions in engineered BNR systems, denitrification is implicated as a potential source of global

N_2O emissions (U.S. EPA, 2009). Although autotrophic nitrification can itself contribute to N_2O emissions from wastewater treatment plants, as will be discussed in Chapter 4.0 of this report and as shown in (Ahn et al., 2009; Kampschreur et al., 2008a), the sole focus of this work was to elucidate potential triggers of N_2O emissions from two distinctly operated heterotrophic denitrifying reactors.

Several factors have been linked to N_2O and NO generation and emission from denitrifying bioreactors including low pH (Focht, 1974), short solids retention time (Hanaki et al., 1992), organic carbon limitation (Hanaki et al., 1992), dissolved oxygen inhibition (Tallec et al., 2008; Park et al., 2000) and nitrite inhibition (von Schultess et al., 1995). However, the impact of the specific carbon source on resulting N_2O and NO generation and emission has received limited attention. From an engineering perspective, with increasing methanol costs, wastewater utilities may adopt alternate external carbon sources, e.g., ethanol, to sustain and enhance denitrification. Even though higher specific denitrification rates might be fostered by these alternatives to methanol, it is imperative to determine associated N_2O or NO emissions to ensure minimization of both aqueous and gaseous nitrogenous pollution. Such an evaluation is especially important since it has been recently shown that different organic carbon sources foster distinct microorganisms, even in mixed cultures (Ginige et al., 2004; Osaka et al., 2008; Baytshtok et al., 2009). Thus, it could be hypothesized that the resulting differences in microbial community structure and their tolerance or susceptibility to transient stressors could give rise to different emissions on different carbon sources.

Therefore, the overall goal of this part of the study was to systematically evaluate N_2O and NO emissions from denitrification using two organic carbon sources, methanol and ethanol in response to three stressors, transient organic carbon limitation, exposure to high nitrite concentration spikes and a range of inhibitory oxygen concentrations.

1.4 Organization of Report

This is an interim report from this project. There is considerable interest in greenhouse gas (GHG) emissions globally. As a result of this interest and the need for research results, WERF will release this interim report with the project findings. The final report, meeting all project objectives, is expected by 2012.

The interim report is presented in the following sections.

CHAPTER 2.0

METHODS AND PROCEDURES - PROTOCOL FOR DETERMINATION OF N_2O EMISSIONS FLUXES AND OTHER ANALYTICAL PROCEDURES

2.1 Introduction

One of the most significant outputs from this project has been the development of a protocol that enables collection of N_2O emission fluxes from open-surface activated sludge bioreactors using consistent methodology. The protocol was submitted to the United States Environmental Protection Agency for review during fall 2008 and the comments provided have been duly incorporated herein. The protocol is intended to provide utilities and field sampling teams with a detailed description of the data collection methodology and analysis requirements to enable calculation of gaseous nitrogen fluxes from different zones of activated sludge trains in a wastewater treatment facility. The protocol was officially released during the 2nd Water Environment Federation Nutrient Removal Conference in Washington DC during June 2009 and is also available online at www.werf.org. The entire protocol is also provided as an appendix as part of this report.

2.2 Sampling Design for Full-Scale Monitoring

The N_2O emission fluxes of several wastewater treatment plants that are accomplishing nitrification and denitrification were determined. Testing was conducted at each plant during which gas phase monitoring was performed in real-time continuous mode and liquid phase sampling was performed via discrete grab sampling. Plants were subjected to two campaigns conducted once in warm temperature conditions (i.e. summer, early fall), and cold temperature conditions (winter/early spring) in the Northeast and Midwest and twice in plants along the West Coast (Fall and Spring), not subject to significant temperature changes.

2.3 Sampling Procedures-Headspace Gas Measurement

The overall procedure for measuring N_2O, NO and NO_2 fluxes from the head-space of activated sludge tanks involves a variant of the EPA/600/8-86/008 and the South Coast Air Quality Management District (SCAQMD) tracer methods. This variant was developed to measure those sources that have a relatively high surface flux rate when compared to diffusion (for instance, spilled oil containment).

Commercially available replicas of the U.S. EPA surface emission isolation flux chamber (SEIFC, Figure 2-1) were used to measure gaseous N fluxes from activated sludge reactors. The SEIFC consists of a floating enclosed space from which exhaust gas is collected in a real-time or discrete fashion. Since the surface area under the SEIFC can be measured, the specific flux of the gaseous compound of interest can be indirectly determined. The SEIFC ‘floats’ on the activated sludge tank surface and several replicate measurements can be taken at different locations in a single tank as well as from different tanks (nitrification, denitrification) along a treatment train.

The SEIFC is also equipped with mixing (physical mixer or via sweep gas circulation) to ensure adequate gas mixing and in some cases, an online temperature probe. The SEIFC is currently one of the few devices accepted by the U.S. EPA for measuring gaseous fluxes (Tata et al., 2003) and as such will be employed for this study. Gas-phase analyses was conducted via infra-red (N_2O) and chemiluminescence (NOx).

In general, sampling was conducted at multiple locations of the activated sludge train in each wastewater treatment facility. These locations included aerobic, anoxic and anaerobic zones, depending upon the configuration of the given facility. During the course of the gas phase sampling, liquid phase samples were collected adjacent to the hood location. The samples were filtered immediately upon collection in the field and analyzed by host plant personnel for ammonia, nitrite and nitrate concentration, utilizing readily available field methods (i.e. Hach kits) and standard laboratory analytical methods.

The specific locations selected were the geometric center of each demarcated anoxic or aerobic zone in the WWTP, or alternately locations where nitrification could be inferred based on initial screening of NH_4^+-N and DO concentrations (as in the plug-flow processes). For discrete measurement at each of these locations, 30 replicate measurements of gaseous N_2O and 1 measurement of aqueous N_2O were obtained over a period of 30 min. During continuous measurement at each of these specific locations over a 24 hour period, gaseous N_2O

concentrations were still measured at 1/min, while aqueous N_2O concentrations were measured four-five times per day. Independent replication at each location (on different days) was not conducted owing to practical limitations associated with such an extensive campaign.

2.4 Sampling Procedures-Aqueous N_2O Concentrations

Aqueous phase N_2O concentrations were measured using a miniaturized Clark-type sensor with an internal reference and a guard cathode (Unisense, Aarhus, Denmark). The sensor is equipped with an oxygen front guard, which prevents oxygen from interfering with the nitrous oxide measurements. The sensor is connected to a high-sensitivity picoammeter and the cathode is polarized against the internal reference. Driven by the external partial pressure, nitrous oxide from the environment will penetrate through the sensor tip membranes and be reduced at the metal cathode surface. The picoammeter converts the resulting reduction current to a signal. The internal guard cathode is also polarized and scavenges oxygen in the electrolyte, thus minimizing zero-current and pre-polarization time.

2.5 Sampling Procedures: Measurement of Advective Gas Flow Rate from Bioreactor Headspace

Advective flow of gas through the flux-chamber ($Q_{emission}$) *in aerated zones* was measured using a modification of ASTM method D1946. Briefly, a tracer gas consisting of 10,000 ppmv ($C_{helium\text{-}tracer}$) He was introduced into the flux-chamber at a known flow rate, Q_{tracer} (equation 1). He concentrations in the off-gas from the flux-chamber ($C_{helium\text{-}FC}$) were measured using a field gas-chromatograph equipped with a thermal conductivity detector (GC-TCD). $Q_{emission}$ was computed using equation 1.

$$Q_{tracer} * C_{helium-tracer} = (Q_{tracer} + Q_{emission}) * C_{helium-FC}$$

$$Q_{emission} = \frac{Q_{tracer} * (C_{helium-tracer} - C_{helium-FC})}{C_{helium-FC}}$$

(Equation 1)

2.6 Determination of Advective Gas Flowrates through the Flux-Chamber from Non-Aerated Zones

The only modification to the protocol to measure the emission flow rate from *non-aerated zones* was the introduction of sweep gas (air) or carrier gas through the flux-chamber at a known flow rate (Q_{sweep}), in addition to the He tracer gas. The corresponding $Q_{emission}$ was computed using Equation 2. Addition of sweep gas is needed to promote mixing of the SEIFC contents, owing to the low advective gas flow from the anoxic-zone headspace. Sweep-air N_2O

concentrations were always measured and typically below the detection limits of the N_2O analyzer.

$$Q_{tracer} * C_{helium-tracer} = (Q_{tracer} + Q_{sweep} + Q_{emission}) * C_{helium-FC}$$

$$Q_{emission} = \frac{Q_{tracer} * (C_{helium-tracer} - C_{helium-FC})}{C_{helium-FC}} - Q_{sweep}$$

(Equation 2)

During continuous N_2O measurements, $Q_{emission}$ was determined several times a day to match liquid-phase N_2O measurements.

2.7 Sampling Procedures-Wastewater and Process Characterization

Preliminary Data Gathering and Steady State Process Analysis. The integral dependence of N_2O and NO emissions on the process operating conditions made the development of a preliminary reconnaissance analysis crucial. The following background information was collected from candidate evaluation sites:

- **Overall Plant Description.** First, general information related to treatment plant configuration, liquid and solids process flow diagrams, design criteria, major mechanical process equipment, etc from the plant's design reports and/or O&M manuals were obtained. In addition, the following secondary process operating data was gathered via meetings with plant operations teams and process engineers:

- **Secondary Process Configuration.** including zone configuration, zone volumes, operating set points, basins in service, aeration flow and distribution, recycle streams and flow rates (if applicable)

- **Plant Operating Data.** Summary of a minimum of three months plant data applicable to the treatment process to allow for characterization of the process influent, target and actual operating setpoints for key operational parameters (DO, SRT), effluent concentrations.

2.8 Intensive On-Site Sampling and Analysis

Intensive diurnal sampling was conducted during each N_2O sampling campaign at the different plants to develop correlations between process state variables and gas-phase N_2O and NOx concentrations (presented in Chapter 3.0). Typical state variables measured, measurement locations and frequency are summarized in the detailed protocol (Appendix A).

2.9 Sample Collection Responsibilities

The measurement of nitrogen GHG emissions and collection of samples using the flux chamber were done by Columbia University researchers and field technicians under the direct supervision of Dr. Kartik Chandran. As the measurement of these parameters were conducted by real-time analyzers or *in-situ* liquid probes, there was no need for sample collection, handling and preservation. The real-time data from the analyzers or probes was automatically downloaded on to a field computer or recorded in laboratory notebooks under the control of the Columbia University researchers. All electronic data were backed up immediately upon return to New York to a duplicate location in the Environmental Biotechnology Laboratories at Columbia University. Additionally, where feasible electronic data was stored on a temporary disk drive (in addition to the PC hard drive) during the field testing events.

2.10 Principles of Real-Time N_2O, NO and NO_2 Measurements

2.10.1 Principles of N_2O Measurement

Continuous N_2O measurements were performed via infra-red (IR) gas-filter correlation, which is based on the absorption of IR radiation by N_2O molecules at wavelengths near 4.5 μm. As part of the measurement process, a broad wavelength IR beam is generated inside the instrument and passed through a rotating gas filter wheel, which causes the beam to alternately pass through a gas cell filled with dinitrogen, (measure cell) and a cell filled with N_2O/N_2 mixture (reference cell) at a frequency of 30 cycles/sec. N_2O concentrations are inferred based on the amount of IR absorption at wavelengths close of 4.5 μm. Ultimately, the 'stripped' beam strikes the detector which is a thermoelectrically cooled solid-state photo-conductor. This detector, along with its pre-amplifier converts the light signal into a modulated voltage signal.

2.10.2 Principles of NO and NO_2 Measurement

The chemiluminescence approach is based on the gas-phase reaction of NO with excess ozone (O_3), which produces a characteristic near-infrared luminescence (broad-band radiation from 500 to 3,000 nm, with a maximum intensity at approximately 1,100 nm) with an intensity that is proportional to the concentration of NO.

Reaction chemistry involved in measurement of NO concentrations

$NO + O_3 \rightarrow NO_2 + NO_2^* O_2$ Formation of stable and excited NO_2 by reaction of NO with O_3

$NO_2^* \rightarrow NO_2 + h\nu$ Conversion of excited NO_2 to stable NO_2 with release of luminescent radiation

Reaction chemistry involved in measurement of NO_2 concentrations

NO_2 + reducing agent → NO + oxidized products Reduction of NO_2 to NO

NO measurement by chemiluminescence (Reactions 1 and 2)

To determine the concentration of NO by chemiluminescence, the sample gas flow from the nitrifying reactors is mixed with O_3 in a reaction chamber operated under negative pressure (vacuum). The chemiluminescence that results from these reactions is monitored by an optically filtered high sensitivity photomultiplier, that responds to NO_2 chemiluminescence emission at wavelengths longer than 600 nm. The electronic signal produced in the photomultiplier is proportional to the NO concentration in the sample gas. Measurement of NO_2 is achieved by means of a heated converter that reduces NO_2 to NO.

2.11 Data “Analysis and Processing

2.11.1 Determination of Fluxes

The net flux of gaseous N species (mg/min-m^2) was calculated based on the gas flow rate out of the flux chamber ($Q_{emission}$, L/min), gas concentration (parts per million) and the cross-sectional area of the SEIFC (m^2) (Equation 3).

$$\mathrm{Flux} = \frac{Q_{emission} * C}{A} \qquad \text{(Equation 3)}$$

2.11.2 Determination of Lumped Emission Fractions

The surface flux calculated from Equation 3 was translated into the flux of a given zone by multiplying with the specific zone area. The N_2O emission fractions (mass/mass) for each WWTP at any given time point were computed by normalizing the measured flux from each zone in the facility to the daily influent total Kjeldahl nitrogen (TKN) loading according to equation 4. Emission fractions were averaged over the course of the diurnal sampling period and reported as the average (avg.) ± standard deviation (sd) for each individual process sampled.

During each campaign, wastewater nitrogen species concentrations including influent, bioreactor and effluent total Kjeldahl nitrogen (TKN), ammonium (NH_4^+-N), nitrite (NO_2^--N) and nitrate (NO_3^--N) were measured simultaneously about six-times per day according to Standard Methods (Eaton et al., 2005) to supplement the gas-phase measurements. The discrete measurements were averaged to generate the emission fractions described in Equation 4. Additionally, seven out of the twelve processes were sampled at minimum and maximum annual wastewater temperatures to examine seasonal temperature impacts on N_2O generation and emission.

$$Emission \quad fraction = \frac{\sum_{i=1}^{n} Flux_i * Area_i \quad (kg \quad N_2O-N)}{Daily \quad \inf luent \quad TKN \quad load \quad (kg-N)}$$

(Equation 4)

Where:

$Flux_i$ = N_2O emission flux calculated from the ith zone (kg N_2O-N/m^2-d)
$Area_i$ = Surface area of the i^{th} zone (m^2)
n = number of zones in a given facility from which N_2O fluxes are captured
Daily influent TKN load: Average influent load (influent flow rate * influent TKN concentrations) over the course of 24 hours.

On average, wastewater characterization was performed at each gas sampling location as well as in the tank influent and effluent about six times per day. At facilities where analysis was not as frequent, daily composite measurements were employed, for instance in the influent and effluent samples. Alternately, in some facilities, online measurement devices (for measuring pH, dissolved oxygen, redox potential and select N-specieis, including NH_4^+-N and NO_3^--N) were employed at different locations of the activated sludge tank, which also facilitated the wastewater characterization efforts.

2.11.3 Calculation of N_2O Emission Factors

N_2O emission factors were computed by normalizing the total reactor N_2O mass flux to the unit population equivalent flow rate (100 gal/PE/day) and were expressed in units consistent with the U.S. EPA inventory report (g N_2O/PE/year) (U.S. EPA, 2009). For aerobic zones, the helium-based advective gas-flow data were correlated to plant-recorded airflow rates for any given zone via linear regression and used to calculate diurnal N_2O emission factors. For anoxic (non-aerated) zones lacking associated plant airflow data, the average of the experimentally obtained helium-based gas flow rates was used to calculate diurnal N_2O emission factors.

2.11.4 Correlation between WWTP Operating Conditions and N_2O Emissions

Possible links between WWTP operating conditions and N_2O emission fluxes were examined via multivariate linear regression modeling of emissions and several wastewater state variables using SAS (Cary, NC). For aerobic zones, N_2O fluxes were correlated with liquid temperature and sampling location-specific pH, temperature, dissolved oxygen (DO), NH_4^+-N and NO_2^--N concentrations and multiplicative combinations thereof. For anoxic zones, N_2O fluxes were correlated with sampling location-specific soluble chemical oxygen demand (sCOD), pH, temperature, DO, NO_2^--N and NO_3^--N concentrations and interactive combinations thereof. Assumptions of state variable normality and equal variance were evaluated using error residual and covariance plots (not shown). The variables not normally distributed were log-transformed, verified for normality and equal-variance and subsequently used for regression modeling. Time points where all state variables had not been measured simultaneously were not included in regression analysis.

2.12 Standardization of Protocol and Comparison with Established Emissions Flux Measurement Methods

The validity of the measurements using the protocol developed for this study was determined via a parallel sampling effort among three teams on September 9 and 10, 2008 at one of the test wastewater treatment facilities. The plant staff used an U.S. EPA flux chamber technology and sampled nitrogen oxide compounds using a field photo-acoustic analyzer. The Columbia University-WERF team used a flux chamber manufactured by St. Croix Sensory and measured N_2O off-gas concentrations via gas-filter correlation, described above. A third team led by Dr. Charles Schmidt used an U.S. EPA flux chamber and sampled the off-gas into opaque Tedlar® bags for FTIR analysis (NIOSH 6660) by a commercial laboratory (Peak Analytical, Boulder, CO).

Based on these parallel measurements, the three methods resulted in similar results (Figure 2-2), with good correspondence in both the nitrous oxide concentrations and off-gas flow-rate (only done by the Columbia-WERF team and Dr. Schmidt's team, Figure 2-3). Briefly, the following observations were made based on the results obtained and incorporated into subsequent full-scale measurement campaigns.

The use of an inert gas tracer was demonstrated to be an appropriate method to determine the advective off-gas flow rate. This was an improvement over the initial method developed by the Columbia-WERF team based on successive dilution of the N_2O concentrations. The initial method was discontinued following the validation study and replaced with He-tracer based method to determine advective flow rate.

Significant spatial and temporal variability in the measured concentrations of headspace N_2O was observed by the Columbia-WERF and Schmidt teams (Figure 2-4). Therefore, for subsequent full-scale measurements, discrete measurements (once a day) of N_2O at different locations in any given WWTP was discontinued. Rather, a substantially more involved sampling strategy that entailed 24-hour “real-time online monitoring” of emissions at each location was initiated. The degree of spatial and diurnal variability in the measurements is further highlighted for four selected WWTPs in Chapter 5.0 in this report. Consequently, in modular systems such as four-pass step-feed BNR reactors, the measurement campaigns lasted for about a week, with pass-by-pass sampling (each lasting 24 hours). Additionally, in select WWTPs where resources permitted, (such as the four-pass step-feed BNR reactor 2 presented in Chapter 3.0), emissions were monitored over a period of five days to explore day-to-day variability.

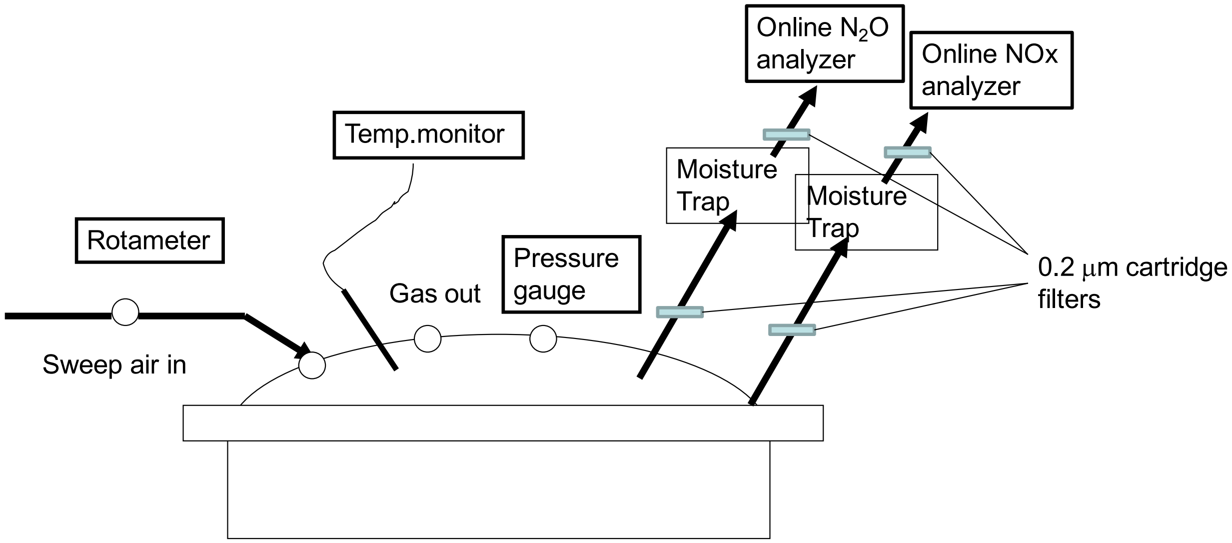

Figure 2-1. Schematic of Flux-Chamber Employed for N_2O Measurement.

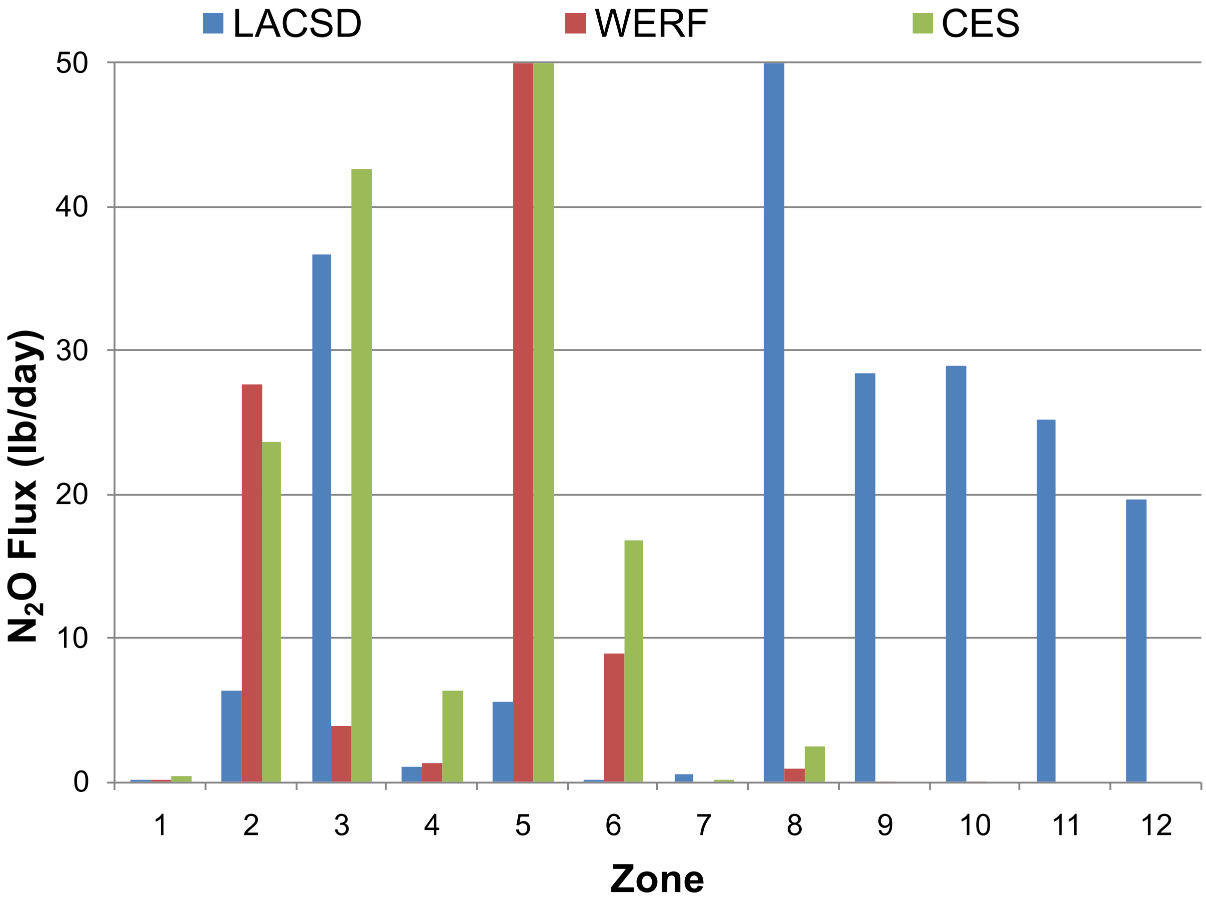

Figure 2-2. Comparison between N_2O fluxes Obtained via Three Independent Methods.

Note: Only the CES and WERF fluxes can be directly compared since they were conducted concurrently.

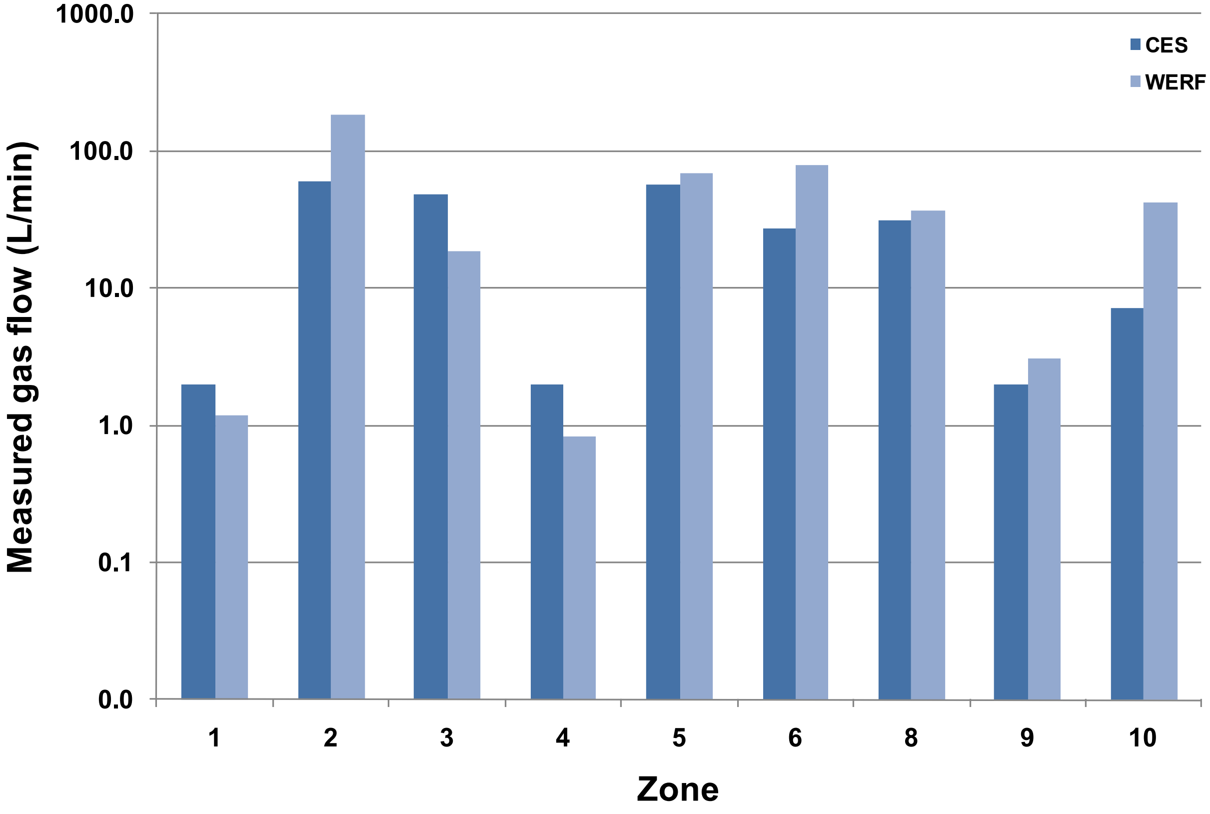

Figure 2-3. Comparison between Gas Flow Rates Obtained via the Tracer Gas (CES) and Successive Dilution (WERF-Columbia) Methods.

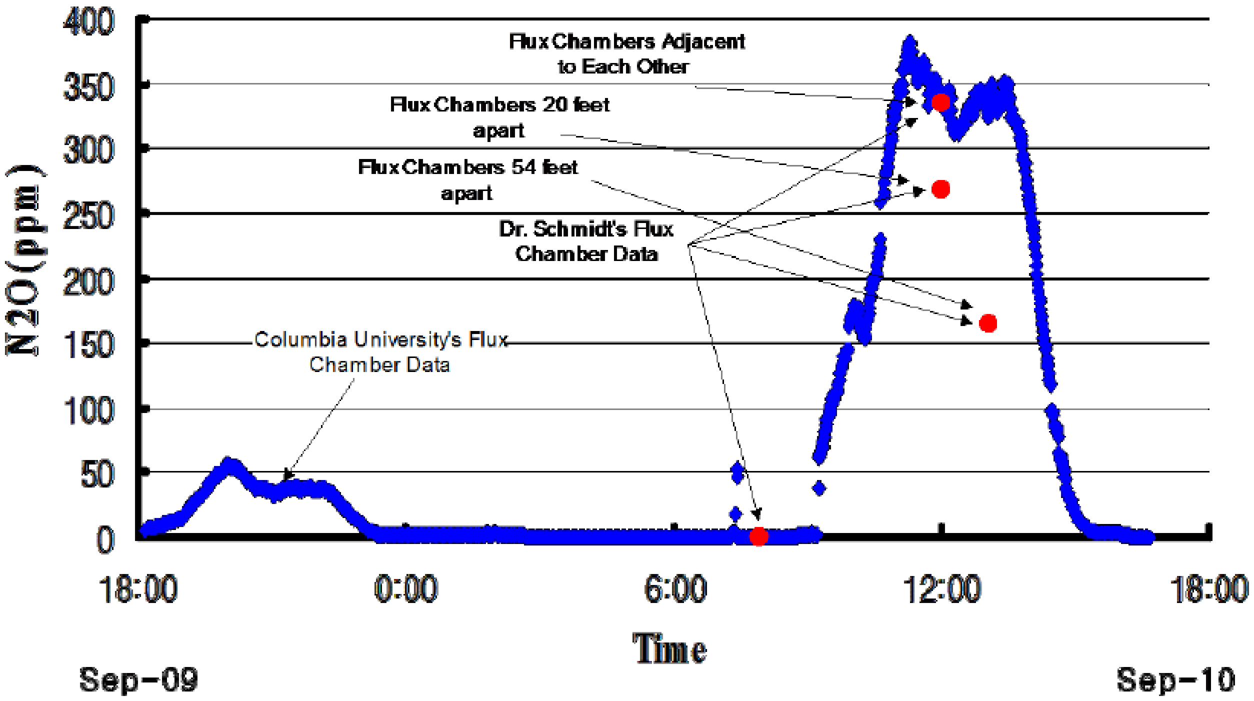

Figure 2-4. Illustration of Spatial and Temporal Variability in N_2O Concentrations in the Headspace of an Aerobic Zone that Necessitates Real-Time Online Monitoring.

Columbia University's flux chamber data given by near continuous blue diamonds.

Dr. Schmidt's flux chamber data given by 4 red dots.

2.13 Sampling and Analytical Methods and Procedures for Pure Culture Lab-Scale Nitrification Studies

2.13.1 Cell Cultivation

N. europaea (ATCC 19718) cultures were cultivated in chemostat mode (V = 4L) in duplicate at a dilution rate of 0.45 d^{-1}. The growth medium was as described previously (Chandran and Love, 2008) and contained 20 mM NH_4^+ and in addition (per liter): 0.2 g of MgSO4•7H_2O, 0.02 g of $CaCl_2$•2H_2O, 0.087 g of K_2HPO_4, 2.52 g EPPS (3-[4-(2-hydroxyethyl)-1-piperazine] propanesulfonic acid), 1 mL of 13% EDTA-Fe^{3+}, 1 mL of trace elements solution (10 mg of Na_2MoO_4•2H_2O, 172 mg of $MnCl_2$•4H_2O, 10 mg of $ZnSO_4$•7H_2O, 0.4 mg of $CoCl_2$•6H_2O, and 100 mL of distilled water), 0.5 mL of 0.5 % phenol red, and 0.5 mL of 2 mM $CuSO_4$•5H_2O. Reactor pH was automatically controlled at 7.5 ± 0.1 using a sterile solution of 40 g/L sodium bicarbonate. The reactor was maintained at 21°C in dark and aerated using filtered air at a constant flow rate of 1.16 L/min. Transient anoxic conditions were imposed by substituting filter sterilized N_2 gas for air at the same gas-flow rate. During the transient anoxic conditions, chemostat cultures were subjected to three different influent NH_4^+ concentrations, 20 mM (equal to the steady-state influent NH_4^+ concentration), 10 mM and 2 mM. Consequently, the impact of different NH_4^+ concentrations accumulated during anoxia on *recovery* back to aerobic conditions could be studied.

NH_4^+ (gas-sensing electrode, Corning, Corning, NY), NH_2OH (Frear and Burrell, 1955), NO_2^- (diazotization, (Eaton et al., 2005), cell concentration (direct counting using a cell counting chamber, Hawksley Scientific, England), gaseous N_2O (gas-filter correlation, Teledyne API 320E, San Diego, CA), NO (chemiluminescence, CLD-64, Ecophysics, Ann Arbor, MI), intracellular NO presence (2’,7’-difluorofluorescein diacetate staining, Molecular Probes, Eugene, OR), dissolved oxygen (Clark-type polarographic electrode, Yellow Springs Inc., Yellow Springs, OH) and specific oxygen uptake rate (sOUR, (Chandran and Love, 2008)) based activity were measured periodically. Direct measurements of liquid-phase N_2O concentrations with a micro-electrode (Unisense, Aarhus, Denmark) were attempted but precluded by interference with dissolved oxygen and possibly NO (data not shown). Hence, liquid-phase N_2O concentrations were calculated via Equation 5.

$$N_2O(l) = \left[\frac{dC_{g,N2O}}{dt} + \frac{Q_g * C_{g,N2O}}{V_g}\right] * \frac{V_g * K_{H,N2O}}{k_{l,a} * V_L} \qquad \text{(Equation 5)}$$

Where:

$N_2O(l)$: numerically computed liquid phase N_2O concentration (mg-N/L)
$C_{g,N2O}$: gas phase concentration of N_2O (atm)
$dC_{g,N2O}/dt$: three point continuously running time derivative of experimentally measured gas phase N_2O concentration, (atm/h)
Q_g: gas flow rate of air or N_2, 69.6 L/h
V_L: liquid volume in reactor, 4L
V_g: headspace gas volume in reactor, 2 L
$K_{H,N2O}$: 42 mg-N/(L-atm) (Dean, 1985)
$k_{l,a}$: average experimentally determined N_2O gas-liquid mass transfer coefficient, 8.2 h^{-1}, (sd = 0.8 h^{-1}, n=4)

2.13.2 Cell Collection and RNA Extraction

At each sample point, 40 mL cell suspensions were collected and immediately centrifuged at 4°C and 5000*g for 10 min. Resulting cell-pellets were resuspended and lysed in 1 mL TRIzol® solution (Invitrogen, Carlsbad, CA). RNA was isolated from lysed cell pellets following the TRIzol® RNA isolation protocol (Invitrogen) and stored at -80°C until further processing.

2.13.3 Functional Gene Expression

Expression of four functional genes coding for NH_4^+ oxidation (*amo* subunit A, *amoA*), NH_2OH oxidation (*hao*), NO_2^- reduction (*nirK*) and the catalytic subunit of the NO reductase cluster (*norB*) was quantified by real-time reverse-transcriptase polymerase chain reaction (q-RT-PCR) using previously documented and newly designed primer sets (see later Table 5-1). These four genes were chosen since they code for the enzymes in the principal oxidative and reductive nitrogen transformations in *N. europaea* (Chain et al., 2003). Additional primers for conventional end-point PCR were also designed for *hao, nir*K and *nor*B and used for preparing standard curves for q-RT-PCR (Table 5.I). Expression of functional genes was normalized to expression of the 16S rRNA gene quantified using primers EUBF and EUBR (Nadkarni et al., 2002).

DNA removal and reverse transcription from total RNA was performed using the QuantiTect® Reverse Transcriptase kit (Qiagen, Valencia, CA). The qPCR and endpoint PCR assays were performed in duplicate on an iCycler iQ™5 (Bio-Rad Laboratories, Hercules, CA). A no-template-control was included for each set of PCR and q-RT-PCR reactions. Standard curves for q-RT-PCR consisted of six decimal dilutions of the respective plasmid DNA, containing a given endpoint PCR product. Plasmid concentrations were quantified (50 Bio 5

UV-Visible Spectrophotometer, Varian, Palo Alto, CA) and translated to copy number assuming 660 Da per base pair of double-stranded DNA (Madigan and Martinko, 2006).

2.13.4 Link between Specific Activity of *N. europaea* Cultures and N_2O Emissions

The applicability of N_2O emissions to gauge the specific activity of nitrifying bacteria has recently been proposed (Burgess et al., 2002; Butler et al., 2009). Along these lines, the ratio of the 'extant' specific activity (q_{ns}) to the maximum specific activity ($q_{max,ns}$) of *N. europaea* was computed based on a multiplicative Monod-model. The model included saturation-type functions to describe NH_4^+ limitation, O_2 limitation and NO_2^- inhibition (as free nitrous acid, HNO_2, Equation 2). Trends in the ratio of $q_{ns}/q_{max,ns}$ were tracked over time and correlated to N_2O emission profiles.

$$\frac{q_{ns}}{q_{max,ns}} = \left(\frac{S_{nh}}{K_{S,nh} + S_{nh}}\right)\left(\frac{S_{O2}}{K_{S,O2} + S_{O2}}\right)\left(\frac{K_{I,NO2-}}{K_{I,NO2-} + S_{NO2-}}\right) \qquad \text{(Equation 6)}$$

Where:

S_{nh}: NH_4^+- concentration (mg-N/L)

$K_{S,nh}$: NH_4^+ half-saturation coefficient, 0.5 mg-N/L (Rittmann and McCarty, 2001)

S_{O2}: dissolved oxygen concentration (mg O_2/L)

$K_{S,O2}$: oxygen half-saturation coefficient, 0.75 mg O_2/L (Guisasola et al., 2005)

S_{NO2-}: NO_2^- concentration (mg-N/L)

$K_{I,NO2-}$: NO_2^- inhibition coefficient, 0.52 mg non-ionized HNO_2-N/L (Vadivelu et al., 2007)

2.14 Sampling and Analytical Methods and Procedures for Mixed Culture Lab-Scale Denitrification Studies

2.14.1 Bioreactor Operation

Two denitrifying SBRs (V = 9.2 L) were operated with methanol and ethanol respectively, using nitrate as the terminal electron acceptor as previously described (Baytshtok et al., 2008; Baytshtok et al., 2009). The target solids retention time (SRT) for both SBRs was 10 days and the hydraulic retention time (HRT) was 1 day. Each SBR had a six-hour cycle comprised of 1 h anoxic feed and react, 3.5 h anoxic react, 0.5 h aerobic mixing (to strip out dinitrogen gas and improve settling), 0.75 h settle and 0.25 h decant phases. SBR phases were automatically controlled via a digital controller (Chrontrol Corp, San Diego, CA). The influent COD and NO_3^--N concentrations for both SBRs were 500 mg chemical oxygen demand (COD)/L (methanol or ethanol) and 100 mg NO_3^--N/L. The pH of the SBRs was automatically controlled in the range of 7.3 ± 0.2 using concentrated hydrochloric acid during steady-state operation, but not during gas measurements, during which, the pH ranged from about 7.3 to 8.1.

2.14.2 Characterization of Steady-State and Transient State Operations

Aqueous and gaseous nitrogen species were measured during individual SBR cycles, corresponding to steady-state or transient operations with carbon limitation, nitrite and oxygen inhibition. Each transient condition was imposed at least three times independently upon each of the two SBRs to obtain a measure of biological reproducibility. The transients were specifically imposed as follows:

Carbon limitation. Methanol or ethanol along with nitrate was provided during the first 0.5h of anoxic feeding phase, followed by 1 h of carbon limitation (but not nitrate limitation) and finally followed by 0.5 h of carbon feeding (without nitrate). In this manner, temporary carbon limitation followed by recovery to non-limiting conditions was imposed. However, the overall carbon and nitrate mass fed during a given SBR cycle during transient limitation and steady-state were identical.

Nitrite inhibition. 10 ml of stock sodium nitrite solution (46 g NO_2^--N/L) was spiked into the SBR during the middle of the feeding phase to achieve a peak NO_2^--N concentration of 50 mg-N/L. Methanol or ethanol and nitrate were fed to the SBR as during steady state.

Dissolved oxygen inhibition. Oxygen inhibition in the SBR was achieved by continuously pumping air (0.5 L/min for DO = 2.5 ± 0.5 mg/L; 1 L/min for DO = 5.1 ± 1.2 mg/L) or pure oxygen (0.5L/min for DO = 9.0 ± 1.1mg/L) during an SBR cycle. Methanol or ethanol and nitrate were fed to the SBR as during steady state.

2.14.3 Headspace N_2O and NO Measurements

Headspace gas collection was performed using a modification of the full-scale protocol for measuring N_2O and NO fluxes from open surface wastewater treatment plants (described above and in (Chandran, 2009)). Gas collection was performed using a custom-made plastic flux chamber (volume = 3.5 L), which was sealed to the SBR body. Sweep air was introduced into the chamber at a flow rate of 4 L/min, except during transient oxygen inhibition, where the sum of the sweep gas flow rate and air (or oxygen) flow rate equaled 4 L/min. Real-time N_2O and NO concentrations (ppmv) in the flux-chamber were measured via gas-filter correlation (Teledyne API, San Diego, CA) and chemiluminescence (Ecophysics, Ann Arbor, MI), respectively. Nitrite (diazotization), nitrate (ion-selective electrode, Accumet®), pH, ORP and DO (Yellow Springs Instruments, Yellow Springs, OH) were measured at 30 min intervals. Reactor and effluent biomass COD concentrations were measured based on standard methods (Eaton et al., 2005). The fraction of influent nitrate emitted as N_2O or NO was determined by numerically integrating the real-time profile of N_2O or NO emission mass flux (Equation 7) and normalizing to mass of nitrate fed during a cycle.

$$M_{\mathrm{N}} = Q \times C \times \frac{MW_N}{V_0} \times t_0 \qquad \text{(Equation 7)}$$

where, M_N is the mass of emitted nitrogen during a cycle as either NO or N_2O (mg-N), Q is the flow rate of sweep air and gas pumped into the flux chamber (4 L/min), C is the accumulated concentration of N_2O or NO during a cycle (ppmv), MW_N is the molecular weight of nitrogen in N_2O and NO (14, 28 g/mol), V_0 is the molar volume of an ideal gas, 24.05 L/mol at 1atm and 22°C and t_0 is the duration of one cycle (6h).

2.14.4 Extant Biokinetics of Denitrification

Batch experiments were conducted as described previously (Baytshtok et al., 2008) to determine denitrification kinetics with methanol and ethanol at steady state and exposure to three DO concentrations: 2, 5 and 9 mg O_2/L (comparable to DO concentrations transiently imposed upon the SBRs). Briefly, 500 mL biomass samples were withdrawn from the SBRs towards the end of the react cycle, washed, and resuspended in nitrate and COD free medium and sparged with N_2 gas to render them anoxic (DO < 0.2 mg/L). Biokinetic assays were conducted by spiking the biomass samples with non-limiting concentrations of nitrate and COD (methanol or ethanol) and tracking the resulting nitrate and nitrite profiles over time. In selected assays, air or pure oxygen was introduced into the batch denitrification vessels, to achieve different DO concentrations. Specific denitrification rates (sDNR) were computed via linear regression of the nitrate depletion profiles *vs* time and normalizing to total biomass COD concentrations.

CHAPTER 3.0

SUMMARY OF PROCESS SCHEMATICS SAMPLED

N_2O emissions were monitored during this study from a wide range of activated sludge processes (both non-BNR and BNR). The modes of operation are summarized in this chapter according to the process configuration. For the sake of confidentiality, the specific locations of these processes are not described. For the sake of geographic representativeness, these processes were broadly distributed around the North-East (4), Mid-Atlantic (2), Mid-West (2), and South-West (4) regions of the United States. The dimensions of the process bioreactors sampled and the sampling locations are further provided in Appendix C of this report. The emissions from these processes are presented in Table 4-1.

Table 3-1. Summary of Process Schematics Sampled.

Plant Configuration	Description
Separate-stage BNR	The low-rate separate-stage nitrification denitrification process at this WWTP was sampled. The process was configured as a sequence of five reactors in series, as shown in Appendix C. The influent to this process consisted of the clarified effluent from an upstream high-rate process, mainly engaged organic carbon removal. The influent was fed in a step-feed fashion to the first two aerobic zones. The last three zones of this process were non-aerated and the second non-aerated zone received methanol to promote denitrification. The effluent channel of this process was aerated prior to secondary clarification.
Four-stage Bardenpho	The four-stage Bardenpho process consisted of pre-denitrification (without external carbon addition) followed by a primary aerated zone, as shown in Appendix C. The effluent of the primary aerated zone was internally recycled to the anoxic zone. Following the primary aerated zone was a de-oxygenation zone to scavenge dissolved oxygen, prior to methanol addition for enhanced denitrification. The final zone in this process was aerated primarily for stripping off the dinitrogen gas produced during denitrification, prior to secondary clarification.
Step-feed BNR 1	The four-pass step-feed BNR process sampled consisted of pre-anoxic zones comprising about 1/3 of the pass volume followed by aerated zones, as shown in Appendix C. The transition zone between each pass was non-aerated to facilitate deoxygenation. The approximate influent flow split was10%-40%-30%-20% to passes A, B, C and D, respectively. Pass A also received pre-settled anaerobic digestion centrate, which constituted approximately 30% of the influent TKN load to the process. Return activated sludge was also fed to Pass A.
Step-feed non-BNR	The step-feed non-BNR process sampled was configured and operated in four-pass step-aeration mode. The process was completely covered primarily for odor control. The headspace off-gases were consolidated and fed to a biofilter. The approximate influent flow split was 10%/40%/30%/20% to passes A, B, C and D, respectively. Return activated sludge was fed to Pass A.
Separate centrate	The separate centrate treatment process was operated to process pre-settled anaerobic digestion centrate and partially convert the influent NH_4^+-N to NO_2^--N. The separate centrate treatment process was operated in plug flow mode, as shown in Appendix C. Effluent from the separate centrate tank was fed to the overall plant return activated sludge line for possible bioaugmentation with primarily ammonia oxidizing bacteria (AOB) and for nitrogen removal via the short-cut nitrite pathway.
Plug-flow 1	The first plug-flow process sampled was designed and operated primarily for organic carbon removal and nitrification and did not have dedicated anoxic zones or external organic carbon addition. The process was configured in four-pass mode, as shown in Appendix C.

Plug-flow 2	The second plug-flow process sampled was also designed and operated for organic carbon removal and nitrification and did not have dedicated anoxic zones or external organic carbon addition. The process was configured in two-pass mode, as shown in Appendix C.
MLE 1	The first modified Lutzack Ettinger (MLE) process sampled was originally designed for operation in enhanced biological phosphorous removal mode, but subsequently operated in MLE mode. As shown in Appendix C, the process consisted of pre-denitrification without external organic carbon addition. Biomass from zone 6, which was aerated, was internally recycled to anoxic zone 2. Return activated sludge was fed to anoxic zone 1.
MLE 2	The second modified Lutzack Ettinger (MLE) process sampled was also originally designed for operation in enhanced biological phosphorous removal mode, but subsequently operated in MLE mode. As shown in Appendix C, the process consisted of pre-denitrification without external organic carbon addition. Biomass from zone 6, which was aerated, was internally recycled to anoxic zone 2. Return activated sludge was fed to anoxic zone 1.
Step-feed BNR 2	The second step-feed process sampled was configured in four-pass mode as shown in Appendix C. Each pass consisted of pre-anoxic zones comprising 1/3 of the pass volume followed by aerobic zones. The approximate influent flow split was50%-30%-20%-0% to passes A, B, C and D, respectively. The anoxic zones were mixed via low intensity pulse aeration. The return activated sludge was fed to Pass A.
Oxidation ditch	The oxidation ditch process shown in Appendix C was operated to achieve simultaneous nitrification and denitrification by operation are uniformly low aeration intensities and dissolved oxygen concentrations. The influent flow to the process was fed to the inner loop and was mixed and circulated using surface mixers. No external organic carbon was added to enhance denitrification. Return activated sludge was fed to the inner loop of the process.
Step-feed BNR 3	The third four-pass step-feed BNR process sampled consisted of pre-anoxic zones comprising about 1/3 of the pass volume followed by aerated zones, as shown in Appendix C. The approximate influent flow split was 33.3%-33.3%-33.3%-0% to passes A, B, C and D, respectively. Pass A also received pre-settled anaerobic digestion centrate, which constituted approximately 40% of the influent TKN load to the process. Return activated sludge was also fed to Pass A. The reactors of this process were also covered and thus only composite measurements of the overall headspace could be performed.

CHAPTER 4.0

RESULTS: NITROUS OXIDE EMISSIONS FLUXES FROM FULL-SCALE ACTIVATED SLUDGE IN THE UNITED STATES

4.1 N_2O Emission Fluxes from Activated Sludge Processes

A wide range of N_2O emissions was measured across the twelve WWTPs operated at different temperatures, configurations and influent characteristics (Table 4-1). On average, N_2O emission fractions varied from 0.01-1.8% or 0.01-3.3%, when normalized to influent TKN load or influent TKN load processed, respectively. These emission fractions were on the lower end of the range reported by previous studies, which varied between 0-15% of influent TKN load (Czepiel et al., 1995; Kampschreur et al., 2008b; Kimochi et al., 1998; Sommer et al., 1998; Sümer et al., 1995; Wicht and Beier, 1995).

In general, N_2O emissions in aerated zones were higher than those in non-aerated zones (Figure 4-1). Therefore the currently held premise that N_2O emissions from WWTPs mostly occur in the anoxic zones (U.S. EPA, 2009) is not accurate. Higher emissions from aerobic zones can be attributed to three possible phenomena: increased air-stripping of N_2O, N_2O production due to oxygen inhibited heterotrophic denitrification or N_2O production by autotrophic nitrification during changes in aeration. While it was not possible to infer the specific contribution of these phenomena to overall emissions from our data set, attempts were indeed made to identify links between principal operating parameters and measured emissions (described in the modeling section).

Computed flow-normalized emission factors also varied in a wide range (Table 4-1), and were mostly statistically higher (at the α=0.05 confidence level) than currently used values of 3.2 g N_2O/PE/yr (non-BNR processes (Czepiel et al., 1995)) or 7.0 g N_2O/PE/yr (BNR processes (U.S. EPA, 2009)). Emission factor values from the separate-stage BNR and oxidation ditch process were statistically lower, (at the α=0.05 confidence level) and the those from the two MLE processes were statistically not dissimilar, (at the α=0.05 confidence level) relative to the current estimates (Czepiel et al., 1995; U.S. EPA, 2009). The high emission factors for the separate centrate treatment process are primarily because centrate streams have disproportionately low flow rates compared to their TKN concentrations. Therefore, the current convention for normalizing emissions factors to wastewater flow rates may not be universally valid due to significant differences in local or global differences in wastewater composition (Tchobanoglous et al., 2003) and is not recommended. Expression of emissions as a fraction of influent TKN load or influent TKN load processed is possibly more appropriate. A high degree of diurnal variability in emission factors was also observed (shown for four select processes in Figure 4-2) and could be linked diurnal variations in influent N-loading as reported (Ahn et al., 2009). Based on the observed variability either diurnally or across the range of WWTPs sampled, the use of a 'single' universal emission factor to calculate N_2O emissions from all wastewater treatment processes is also inadequate.

4.2 Model Based Discrimination of Process Operating Conditions Contributing to N_2O Emission

Aerobic zones: Based on multivariate regression modeling, the factors correlated positively with N_2O emissions from aerobic zones, were NH_4^+-N, NO_2^--N and DO concentrations (isolated effect), and NH_4^+-N and NO_2^--N concentrations (interactive effect, Table 4-2). From a fundamental perspective, nitrite is one of the most important factors contributing to N_2O production from nitrification (Beaumont et al., 2005; Beaumont et al., 2004b; Beaumont et al., 2004a). Thus, correlation of NO_2^--N concentrations with aerobic zone N_2O emissions is consistent with basic biochemical principles. Although it was previously proposed that low DO concentrations were directly responsible for autotrophic nitrification-related N_2O emissions (Tallec et al., 2006), recent results suggest that N_2O is generated by *recovery* from low DO conditions rather than *imposition* thereof (Yu et al., 2010). In fact, abrupt increases in DO concentrations in the presence of NH_4^+ can also lead to transient accumulation of NO_2^-, which can in turn result in autotrophic NO and N_2O generation (Kampschreur et al., 2008a; Yu et al., 2010). The magnitude of autotrophic nitrification driven N_2O emissions also depends directly on NH_4^+-N concentrations (Yu et al., 2010). Therefore, the positive correlation of NH_4^+-N and DO concentrations individually with N_2O emissions in the aerobic zones is in congruence with this new understanding of aerobic autotrophic N_2O production (Yu et al., 2010). The positive interactive correlation between NH_4^+ and NO_2^- concentrations and N_2O emissions suggests high N_2O emissions from aerobic zone locations, with *simultaneously* high concentrations of both NH_4^+ and NO_2^-. This interactive correlation also points to autotrophic N_2O generation mechanisms, since both NH_4^+ and NO_2^-- are co-substrates in autotrophic denitrification by nitrifying bacteria (Beaumont et al., 2005; Beaumont et al.; 2004b, Beaumont et al., 2004a).

It should be noted that while nitrification dominates N-cycling in aerobic zones, the possibility of heterotrophic denitrification within activated sludge flocs even under ‘bulk’ aerobic conditions cannot be discounted (Grady et al., 1999). Interestingly, as with nitrification, denitrification driven N_2O emissions are also caused by high DO and NO_2^--N concentrations (Korner and Zumft, 1989; Park et al., 2000; von Schultess et al., 1995; Tallec et al., 2008; Zumft, 1997), among other factors. Thus aerobic zone N_2O emissions might be linked to both nitrification and denitrification, although it is not possible to differentiate between the two using bulk headspace measurements alone. (von Schultess et al., 1995)

Anoxic zones: Several factors have been implicated in N_2O and NO generation and emission from denitrifying bioreactors, such as low pH (Focht, 1974), short solids retention time (Hanaki et al., 1992), organic carbon limitation (Hanaki et al., 1992; von Schultess et al., 1995; von Schultess et al., 1994), DO inhibition (Tallec et al., 2008; Park et al., 2000) and NO_2^--N inhibition (Korner and Zumft, 1989; von Schultess et al.;1995, Zumft, 1997). Inhibition of denitrification by high DO concentrations could also lead to NO_2^--N build-up, indirectly leading to N_2O emissions (Hanaki et al., 1992; Zhou et al., 2008). Thus, the positive correlation of DO and NO_2^--N concentrations with N_2O emissions (Table 4-3) is consistent with known mechanisms of denitrification-related N_2O production. Soluble COD concentrations in anoxic zones were mostly non-limiting and expectedly did not correlate with N_2O emissions. A better correlation would be expected with readily biodegradable COD concentrations (rbCOD). However, rbCOD is analytically difficult to measure in the matrix of activated sludge. Thus, a sound inference on organic carbon limitation and N_2O emissions from the full-scale WWTPs cannot be made. To address the issue of COD limitation on denitrification-related N_2O emissions better, lab-scale studies were conducted, as described in Chapter 6.0.

The regression model did not correlate temperature and N_2O fluxes in either aerobic or anoxic zones (Tables 4-2 through 4-3). A possible reason could be that N_2O fluxes are indirectly governed by temperature through manifestation in NH_4^+-N, NO_2^--N or DO concentrations, described above.

While several factors relevant to activated sludge processes including NH_4^+, NO_2^-, DO, temperature, COD limitation can all lead to N_2O emissions, it may be difficult to discern their specific contributions from highly noisy full-scale data from multiple plants, each operated under different modes and temperatures. Therefore, it is noteworthy that N_2O emissions in aerobic and anoxic zones could be correlated with select specific factors and explained via mechanistic arguments. Further, all model parameter estimates except the intercept of the anoxic zone were statistically valid at the α=0.05 confidence level (Tables 4-1 through 4-2). Nevertheless, it should be noted that the developed model is not a conclusive mechanistic descriptor of causative biological processes contributing to N_2O emissions from activated sludge. Caution is also advised with respect to predicting emissions on the basis of process configuration alone. The factors correlating with N_2O emissions, (NH_4^+-N, NO_2^--N and DO concentrations) are inherently linked with process parameters such as TKN loadings, SRT and wastewater composition. Therefore, the propensity for N_2O emissions of any given WWTP configuration can only be evaluated within the framework of its process operation and performance characteristics.

4.3 Spatial and Temporal Variability in N_2O Generation and Emission from Selected Full-Scale BNR and non-BNR Processes

4.3.1 Spatial and Temporal Trends in N_2O Emission Fluxes from Full-Scale WWTPs

A wide range of N_2O emission fluxes was observed over the course of the monitoring campaign at different BNR and non-BNR activated sludge facilities (Table 4-1). At the first two facilities sampled, both discrete short-term (lasting about 30 min) and continuous (lasting 24 hours) N_2O measurements were conducted in multiple locations or zones (Figure 4-3). However, subsequently, the 30 min discrete measurements are not reported, since they did not capture the considerable temporal variability observed in each zone (for instance, as shown in Figure 4-4). For following campaigns, each location or zone was subjected only to 24 diurnal continuous monitoring (Figures 4-7 through 4-10). The results of the campaigns are summarized below systematically according to the plant operating configurations. For the sake of illustrating spatial and temporal variability, the following subset of the overall sampling set was used:

- Four-pass step-feed BNR process sampled in fall 2008
- Four-stage Bardenpho process sampled in winter 2009
- Low-rate separate stage nitrification-denitrification process sampled in winter 2009
- Two plug-flow processes sampled in winter 2009
- Four-pass step-feed process with covered aeration tanks sampled in winter 2009

4.3.2 Four-Pass Step-Feed BNR Process

Based on discrete sampling conducted in different zones of the four-pass step-feed process, in general higher gas-phase and liquid phase N_2O was measured in the aerobic zones, especially in was also observed (Figure 4-4).

Based on known microbial pathways responsible for N_2O generation by bacteria engaged in BNR reactions, three different potential hypotheses can be put forth to explain these trends in N_2O emissions.

(1) At the transition point between the first-anoxic and aerobic zones, it is possible that both nitrification and heterotrophic denitrification contribute to N_2O emissions. Heterotrophic N_2O emissions could be related to oxygen inhibition (Knowles, 1982; Korner and Zumft, 1989; Zumft, 1992; Hanaki et al., 1992) experienced by heterotrophic denitrifying bacteria at the transition between the anoxic and aerobic zones. This reasoning is supported by the parallel trends in the diurnal DO concentrations and N_2O headspace concentrations (For instance, in Figure 4-5).

(2) The abrupt direction transition from anoxic to aerobic conditions (in the presence of non-limiting NH_4^+ and DO concentrations) also leads to N_2O generation by nitrifying bacteria. According to recent results, N_2O generation by ammonia oxidizing bacteria is related to their recovery from anoxic periods and transient imbalances at the gene expression and metabolic levels (Yu et al., 2010). Thus, autotrophic reactions could potentially contribute to the observed N_2O fluxes at the transition between the upstream anoxic and oxic reactors.

(3) The high liquid and gaseous N_2O concentrations observed at the transition of the anoxic and aerobic zones could also be a carryover from the preceding anoxic zone.

At this stage, the individual contribution of each of these factors to overall measured N_2O emissions cannot be determined and further studies to discriminate between autotrophic and heterotrophic N_2O production are needed.

4.3.3 Four-Stage Bardenpho Process

Based on discrete and continuous measurements, the highest generation and emission of N_2O occurred at two distinct locations. The first location was at the point of transition between the first-anoxic and aerobic zones (Figure 4-5). The second location was near the effluent end of the aerobic zone (Figure 4-5, aerobic zone 2, diurnal data for this location not shown). The emissions of N_2O from the anoxic zones were generally statistically lower ($p < 1.0 * 10^{-4}$ for all two-tailed t-test comparisons $\alpha=0.05$ for this WWTP) and less variable than in the aerobic zones (Figure 4.4). A positive although delayed correlation between NH_4^+, NO_3^- and gaseous N_2O concentrations was observed in the aerobic zone (Figure 4-6). At the same time, increasing DO concentrations also correlated well with aerobic zone N_2O emissions (Figure 4-6). The diurnal variability in anoxic zone N_2O emissions was much lower and did not correlate with liquid phase nitrogen species or DO concentrations (Figure 4-6).

4.3.4 Low-Rate Separate Stage Nitrification-Denitrification Process

The low-rate process sampled is located downstream of a high-rate carbonaceous oxygen demand (COD) removal process, which is scheduled for a future sampling campaign.
The N_2O emissions in the low-rate process were much lower than in any of the others tested. The degree of diurnal variability from this process was also much lower than those in others sampled (Figure 4-7). During diurnal sampling, little correlation between N_2O concentrations and aqueous nitrogen species, dissolved oxygen concentrations or filtered-flocculated chemical oxygen demand (ffCOD) concentrations could be discerned (data not shown) possibly due to the low emission levels. Nevertheless, gaseous N_2O concentrations in the aerobic zones were statistically higher than those in the downstream anoxic zones (Figure 4-7, $p = 0$ for all two-tailed t-test comparisons at $\alpha = 0.05$). These emissions are lower than those measured in a separate nitrification stage of an activated sludge treatment plant measured in the Netherlands (Kampschreur et al., 2008b).

It is believed that the unique configuration and operation of this process contributed to its low N_2O footprint and can be explained in the following manner. First and foremost, the low degree of diurnal variability in the influent nitrogen to this process (which is dampened by a preceding high-rate carbonaceous removal process) could have led to the low degree of temporal variability in emissions. Secondly, the sequence of anoxic zones following the primary aerobic zones is singular to this process. Based on lab-scale studies, nitrifying bacteria produce N_2O in a directional fashion (Yu et al., 2010), when they are shifted from a low DO concentration to a high DO concentration in the presence of non-limiting NH_4^+ concentrations. Such a transition (but without the dependency on NH_4^+) is also responsible for heterotrophic N_2O production, if factors such as rbCOD limitation occur (as seen in the four-stage Bardenpho process, Figures 4-5 and 4-6). Based on the configuration of this specific process, the unique conditions (individually or in combination) that give rise to a combination of these above factors promoting autotrophic or heterotrophic N_2O production were all missing, which could explain the relatively lower N_2O emissions. These observations highlight the need for further development and validation of specific BNR designs that minimize both liquid-phase and gaseous phase nitrogen emissions.

4.3.5 Plug-Flow Processes

Both plug-flow processes sampled are primarily configured and operated for COD removal and nitrification. However, the influent end of both plug-flow processes is typified by oxygen limiting conditions during parts of the day, which could possibly support simultaneous nitrification and limited denitrification (as suggested by the DO concentrations in Figures 4-8 and 4-9).

Based on initial inferences related to the occurrence of nitrification over the entire tank, two sampling points were chosen, one in the middle of pass1 and the second in the middle of pass 2 (Figures 4-8 and 4-9). N_2O emission was higher in the middle region of the second pass of both plug-flow bioreactors, in the presence of non-limiting ammonia and DO concentrations, where nitrification is expected to dominate nitrogen cycling reactions. However, liquid-phase N_2O concentrations at both the influent end and middle regions of the passes were statistically similar (p=0.26 and 1.0, respectively for two-tailed t-test comparisons at $\alpha = 0.05$ for the two processes). The relatively lower levels of N_2O in the influent end of the reactor were possibly due to the N_2O reducing activity of denitrifying heterotrophic bacteria therein (Figures 4-8 and 4-9). Thus, promoting the co-culture and concerted activity of nitrifying and denitrifying bacteria through appropriate BNR configurations seems essential for the mitigation of biogenic N_2O from wastewater treatment plants. Notwithstanding the relative magnitudes of relative N_2O generation and emission, consistent patterns and trends were observed in the two plug-flow processes sampled in this study (Figures 4-8 and 4-9).

4.3.6 Four-Pass Step-Deed (non-BNR) Process (covered aeration tanks)

The main objective of this plant is COD removal, although based on annual plant data, intermittent nitrification is observed during warmer temperatures. The aeration tanks in this plant are covered to minimize odors. The headspace gases from the aeration tanks are combined and treated in a scrubber.

Due to limited access to the individual covered activated sludge bioreactors, the overall scope of this campaign was focused on determining the magnitude of N_2O emissions as a fraction of the influent TKN load. Spatial variability in N_2O emissions could not be inferred. During the diurnal sampling campaign, the headspace N_2O levels were also quite variable and ranged from 1.0-43 ppmv, resulting in an especially high variability in the emissions flux (Figure 4.10). Given the lack of detailed reactor specific chemical profiling as performed for other facilities and the fact that the headspace gases were gathered and sampled collectively, it was not possible to directly implicate the biological reactions contributing to the observed emissions.

4.4 Conclusions

A high degree of variability in field-scale measurements of N_2O was observed, both across the WWTPs sampled and within each WWTP. Additionally, aerobic zones, which have hitherto not been considered in the U.S. EPA approach of estimating N_2O emissions, generally contributed more to N_2O fluxes than anoxic zones from BNR reactors. These results severely qualify the conventional use of a single emission factor to ‘estimate’ N_2O emissions from BNR processes solely by virtue of denitrification. Upon subjecting the nationwide dataset to multivariate regression data mining, high nitrite, ammonium and dissolved oxygen concentrations were positively correlated with N_2O emissions from aerobic zones of BNR reactors. On the other hand, high nitrite and dissolved oxygen concentrations were positively correlated with N_2O emissions from anoxic zones. Based on these results, it can be argued that BNR processes that minimize transient or permanent build up of ammonium or nitrite, especially in the presence of dissolved oxygen, are expected to have low N_2O emissions.

Further information on the mechanisms and triggers for N_2O emissions from WWTPs needs to be developed and included in mechanistic process models that will enable WWTPs to sustainably minimize both liquid effluent and gaseous nitrogen emissions. These mechanisms are the focus of the lab-scale studies presented next in Chapters 5.0 and 6.0.

Table 4-1. Summary of N_2O Fluxes and Emission Factors Measured at Full-Scale WWTPs.

Plant Configuration	Temp(°C)	Reactor influent TKN load (g-N/day)	Reactor effluent TN load (g-N/day)	Q (MGD)	% influent TKN emitted as N_2O	% TN removed emitted as N_2O	Emission factor (g N_2O/PE/yr)
Separate-stage BNR	15 ± 0.48	1.8 x 10^6	3.6 x 10^5	23	0.03 ± 0.00	0.03 ± 0.01	1.2 ± 0.18
	23 ± 0.28	2.3 x 10^6	4.3 x 10^5	27	0.01 ± 0.00	0.01 ± 0.00	0.28 ± 0.13
Four-stage Bardenpho	14 ± 0.26	8.6 x 10^5	1.7 x 10^5	7.8	0.16 ± 0.10	0.19 ± 0.12	9.8 ± 6.1
	23 ± 0.20	7.4 x 10^5	7.6 x 10^4	8.1	0.60 ± 0.29	0.66 ± 0.32	33 ± 16
Step-feed BNR 1	19 ± 0.22	3.1 x 10^6	1.4 x 10^6	29	1.6 ± 0.83	2.9 ± 1.5	92 ± 47
	25 ± 0.28	2.9 x 10^6	9.4 10^5	30	0.62 ± 0.27	0.90 ± 0.39	33 ± 14
Step-feed non-BNR	17 ± 0.12	8.6 x 10^6	4.4 x 10^6	71	0.18 ± 0.18	0.37 ± 0.36	13 ± 13
	26 ± 0.81	8.9 x 10^6	4.2 x 10^6	93	1.8 ± 0.79	3.3 ± 1.5	97 ± 43
Separate centrate*	30 ± 2.3	8.8 x 10^6	5.5 x 10^6	2.0	0.24 ± 0.02	0.63 ± 0.06	*
	34 ± 0.32	8.5 x 10^6	4.2 x 10^6	1.6	0.54 ± 0.16	0.96 ± 0.32	*
Plug-flow 1	11 ± 0.20	1.8 x 10^6	1.0 x 10^6	18	0.40 ± 0.14	0.92 ± 0.32	23 ± 7.9
	23 ± 0.46	1.8 x 10^6	7.3 x 10^5	15	0.41 ± 0.14	0.70 ± 0.24	28 ± 9.6
Plug-flow 2	11 ± 0.41	6.3 x 10^5	4.0 x 10^5	8.7	0.62 ± 0.15	1.7 ± 0.41	26 ± 6.4
	22 ± 0.58	6.6 x 10^5	4.0 x 10^5	6.6	0.09 ± 0.03	0.22 ± 0.06	5.0 ± 1.4
MLE 1	26 ± 1.8	6.8 x 10^5	1.9 x 10^5	4.0	0.07 ± 0.04	0.09 ± 0.05	6.8 ± 3.5
MLE 2	26 ± 0.17	6.9 x 10^5	1.5 x 10^5	4.1	0.06 ± 0.02	0.07 ± 0.03	5.4 ± 2.0
Step-feed BNR 2	29 ± 0.18	2.2 x 10^6	2.9 x 10^5	14	1.5 ± 0.02	1.7 ± 0.02	140 ± 1.2
Oxidation ditch	19 ± 0.58	3.9 x 10^5	4.3 x 10^4	3.4	0.03 ± 0.01	0.03 ± 0.01	1.8 ± 0.77
Step-feed BNR 3	24 ± 0.78	7.8 x 10^6	8.6 x 10^5	57	0.05 ± 0.03	0.06 ± 0.03	4.1 ± 2.2

*: Flow normalized emission factors for centrate are inappropriate since centrate constitutes a miniscule flow rate, while containing up to 30% of the influent TKN load.

Table 4-2. Factors Correlating with N_2O Emission Fluxes (g N_2O-N/day) from Aerobic Zones.

Variable	Parameter estimate	Standard error	t value	Pr > |t|
Intercept	6.1	0.48	13	0.00
Log(ammonia)	1.0	0.25	4.1	0.00
Log(nitrite)	0.60	0.16	3.7	0.00
Log(DO)	0.59	0.18	3.2	0.00
Log(ammonia)-log(nitrite)	0.18	0.08	2.3	0.03

Table 4-3. Factors Correlating with N_2O Emission Fluxes (g N_2O-N/day) from Aerobic Zones.

Variable	Parameter estimate	Standard error	t value	Pr > |t|
Intercept	-1.2	0.89	-1.3	0.21
Log(DO)-log(nitrite)	0.67	0.25	2.7	0.01

Table 4-4. Comparison of N_2O Emissions from Full-Scale Studies Conducted to Date.

Process	Proportion of influent TKN emitted as N_2O (%)	Reference
Activated sludge (11,000 p.e.)	0.035	(Czepiel et al., 1995)
Nitritation-anammox	2.3	(Kampschreur et al., 2008b)
Separate nitrification stage (620,000 p.e.)	4.0	(Kampschreur et al., 2008b)
Activated sludge (1,000 p.e.)	0.01 – 0.08	(Kimochi et al., 1998)
Activated sludge (60,000 p.e.)	0.02	(Sommer et al., 1998)
Activated sludge (60,000 p.e.)	0.001	(Sümer et al., 1995)
Study of 25 activated sludge processes	0-15	(Wicht and Beier, 1995)
Study of BNR and non-BNR activated sludge processes (range of average emissions)	0.01-1.8	This study

Figures

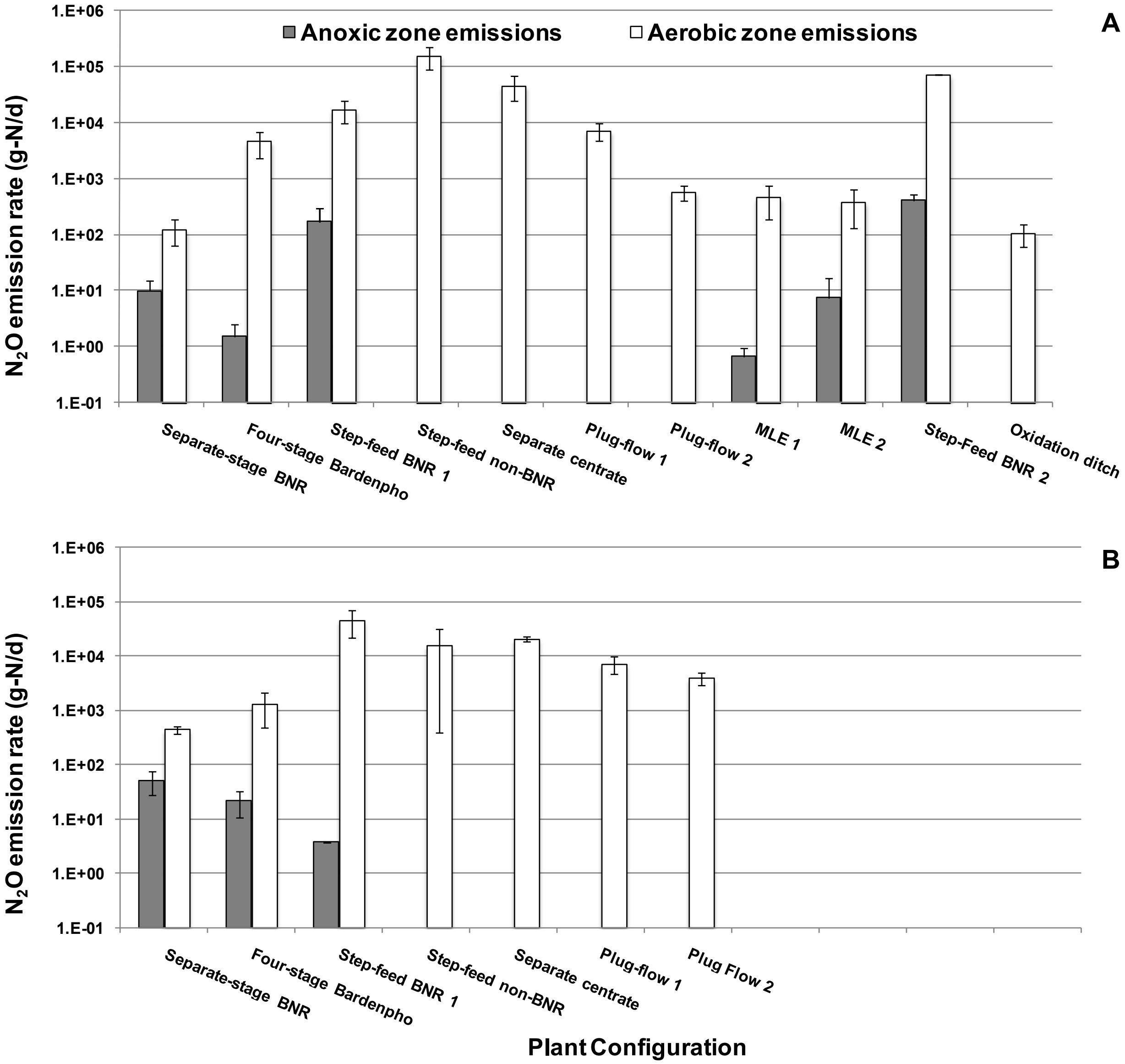

Figure 4-1. N$_2$O Emissions from Aerobic and Anoxic Zones in Different WWTPs Measured at High (A) and Low (B) Temperatures. Specific temperatures described in Table 4-1. Step-feed BNR 3 is not included since the emissions from the covered aerobic and anoxic zones could not be distinctly measured.

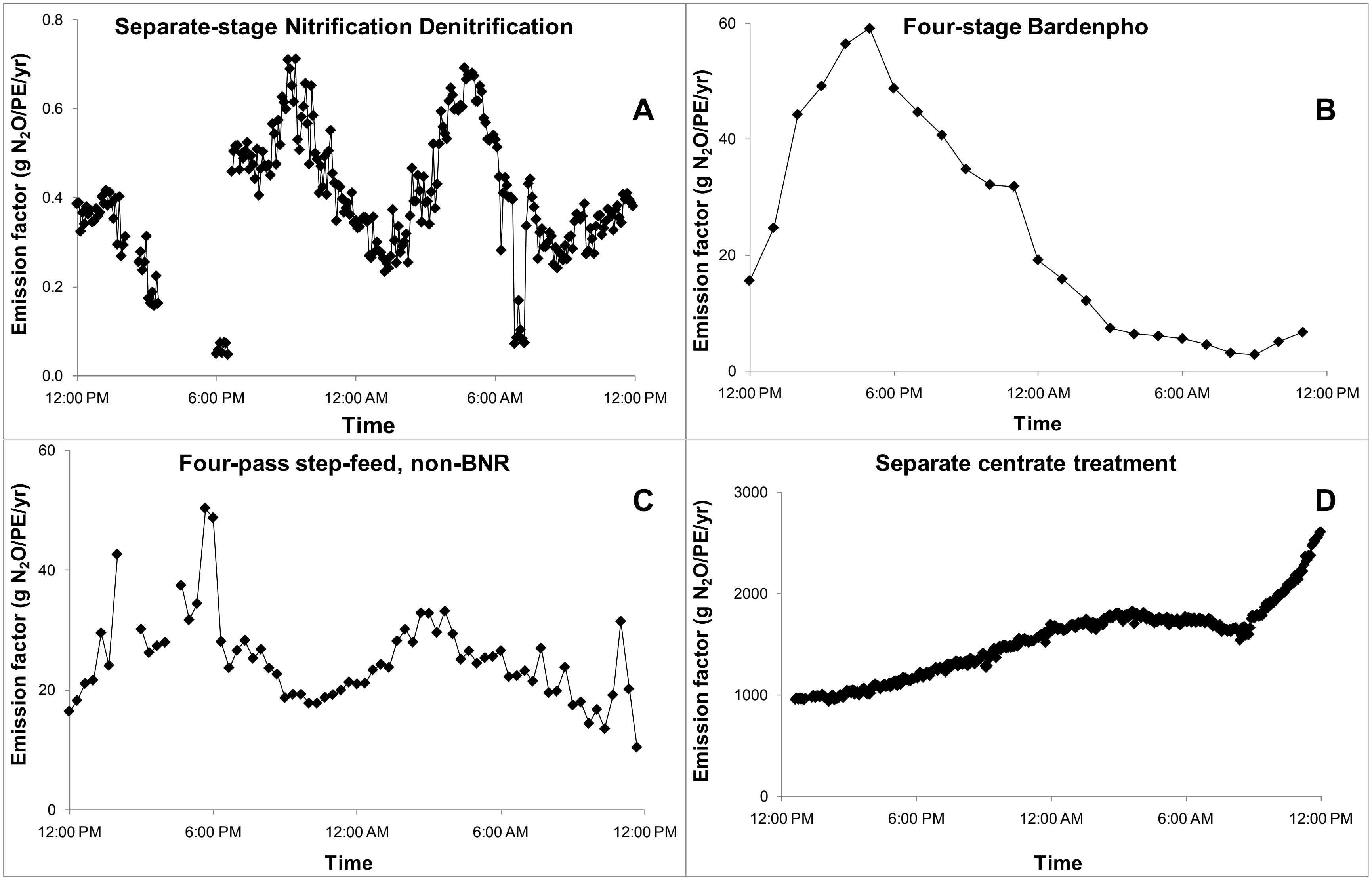

Figure 4-2.Time-Varying N_2O Emission Factors for Four Select Processes Sampled in this Study at 23 ± 0.28°C (A), 23 ± 0.20°C (B), 26 ± 0.81°C (C) and 34 ± 0.32°C (D).

Species	Anoxic →	Aerobic 1 →	Aerobic 2 →
NH_4^+ (mg-N/L)	14	12 ± 5	1.5 ± 0.71
NO_2^- (mg-N/L)	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
NO_3^- (mg-N/L)	0.85 ± 0.10	2.7 ± 0.35	10 .± 0.21
DO (mg O_2/L)	0.10	2.3	4.2
Aqueous N_2O (µg/L)	55	190	570
Gaseous N_2O (ppmv)	1.5 ± 0.14	16 ± 0.27	23 ± 0.67

Figure 4-3. Spatial Profile of Gaseous N_2O Concentrations and Typical Activated Sludge Variables in a Full-Scale Step-Feed BNR Process Showing Individual Sampling Locations.

Results are from discrete sampling over a period of 30 minutes at each sampling point. Arrows indicate wastewater flow. Shaded and unshaded boxes represent non-aerated and aerated zones, respectively. Gaseous N_2O concentrations are expressed as avg. ± sd. of 30 measurements.

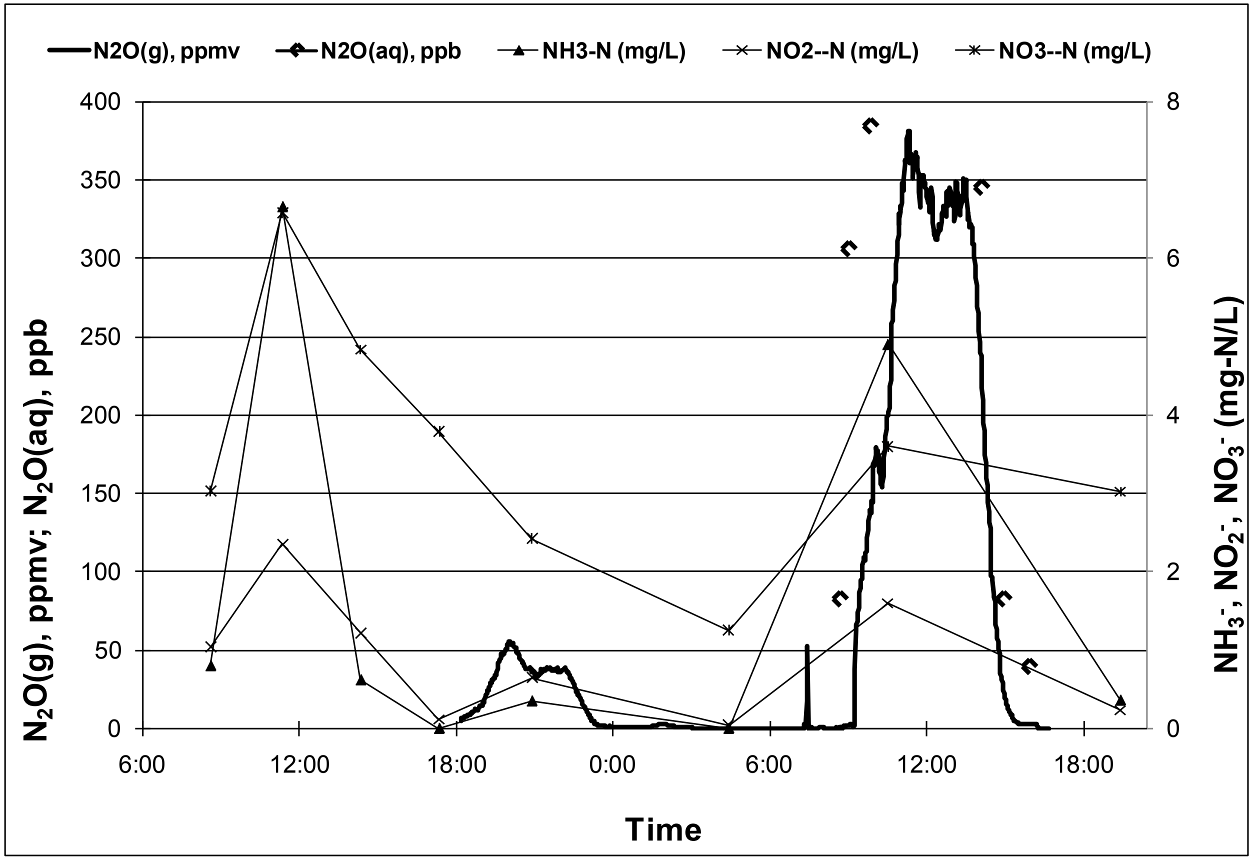

Figure 4-4. Diurnal Variability in Gaseous N_2O Concentrations Measured from an Aerobic Zone of the Full-Scale Step-Feed BNR Process Depicted in Figure 4-3.

Species	Anoxic →	Aerobic 1 →	Aerobic 2 →	Anoxic 1 →	Anoxic 2 → (methanol)	Aerobic 3 →
NH_4^+ (mg-N/L)	**4.9**	**3.2**	**0.50**	**0.30**	**0.0**	**0.0**
NO_2^- (mg-N/L)	**0.10**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
NO_3^- (mg-N/L)	**5.2**	**6.9**	**9.6**	**7.3**	**3.6**	**3.1**
DO (mg O_2/L)	**0.16**	**5.2**	**4.0**	**0.21**	**0.17**	**4.9**
Aqueous N_2O (µg/L)	**22**	**27**	**22**	**12**	**17**	**17**
Gaseous N_2O (ppmv)	**1.2 ± 0.10**	**1.8 ± 0.00**	**2.4 ± 0.14**	**1.0 ± 0.10**	**0.69 ± 0.00**	**1.1 ± 0.00**

Figure 4-5. Spatial Profile of Gaseous N_2O Concentrations and Typical Activated Sludge Variables in a Full-Scale Four-Stage Bardenpho Process.

Results are from discrete sampling over a period of 30 min at each sampling point. Arrows indicate wastewater flow. Shaded and unshaded boxes represent non-aerated and aerated zones, respectively. Gaseous N_2O concentrations are expressed as avg. ± sd. of 30 measurements.

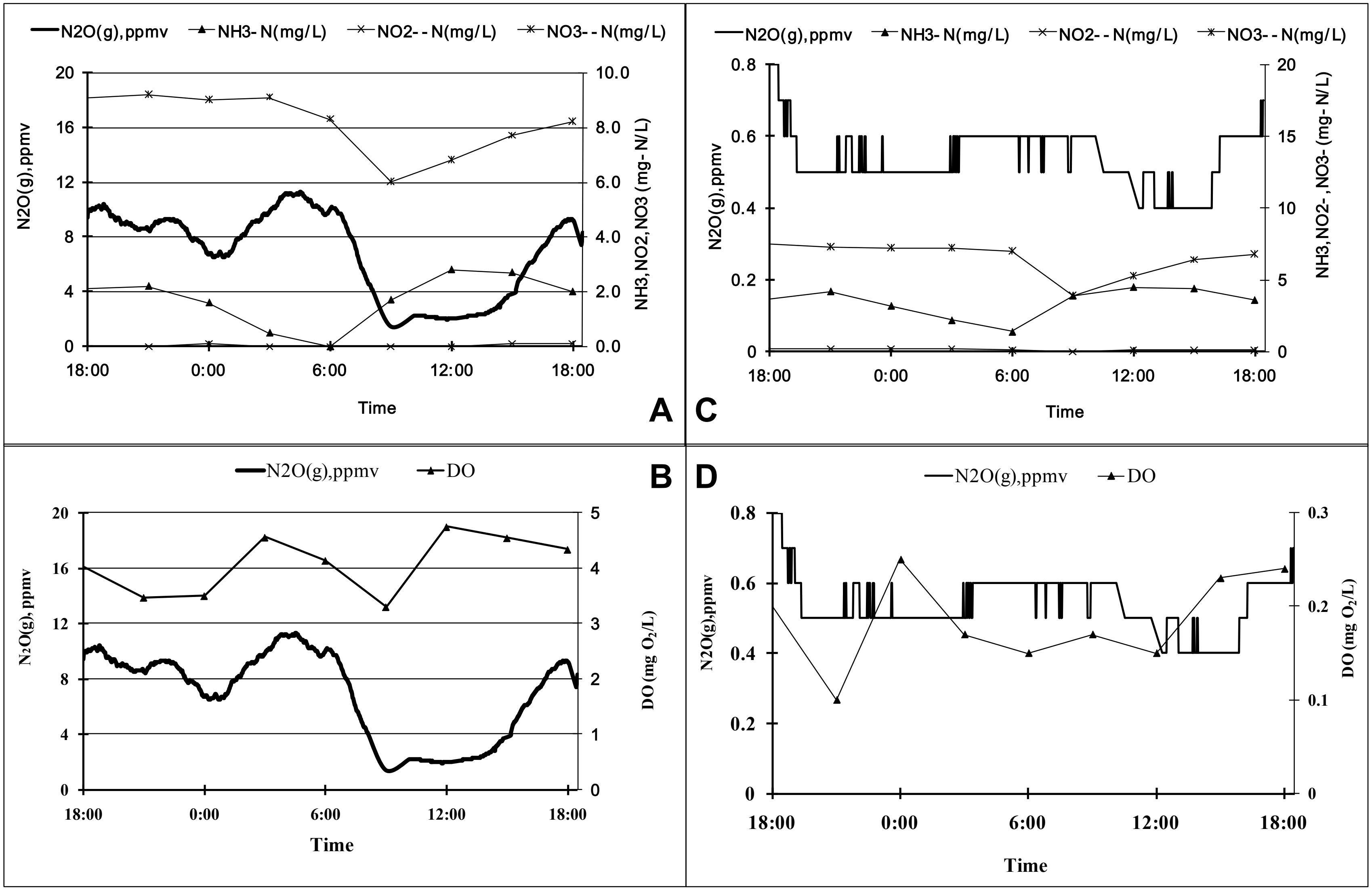

Figure 4-6. Diurnal Variability in Gaseous N_2O Concentrations Measured from the First Aerobic Zone (A-B) and First Anoxic Zone (C-D) of the Full-Scale Four-Stage Bardenpho Process Depicted in Figure 4-4.

Species	Aerobic 1 →	Aerobic 2 →	De-oxic →	Anoxic → (methanol)
NH_4^+ (mg-N/L)	**4.5 ± 2.9**	**5.1 ± 3.6**	**0.57 ± 0.71**	**1.6 ± 1.1**
NO_2^- (mg-N/L)	**0.00 ± 0.00**	**0.10 ± 0.00**	**0.00 ± 0.00**	**0.10 ± 0.00**
NO_3^- (mg-N/L)	**4.9 ± 1.5**	**5.1 ± 1.4**	**7.7 ± 0.60**	**5.5 ± 1.9**
DO (mg O_2/L)	**2.7 ± 0.99**	**2.0 ± 0.54**	**0.81 ± 0.68**	**0.40 ± 0.19**
Aqueous N_2O (µg/L)	**21 ± 3.8**	**24 ± 15**	**19 ± 9.8**	**16 ± 7.8**
Gaseous N_2O (ppmv)	**3.0 ± 0.36**	**3.4 ± 1.1**	**1.3 ± 0.31**	**1.1 ± 0.15**

Figure 4-7. Spatial Profile of Gaseous N_2O Concentrations and Typical Activated Sludge Variables in a Full-Scale Separate-Stage Nitrification-Denitrification Process.
Results are from diurnal sampling over a period of 24 hours at each sampling point. Arrows indicate wastewater flow. Shaded and unshaded boxes represent non-aerated and aerated zones, respectively. The lightly shaded box represents a deoxic transition zone, which is also not aerated.

Species	Aerobic 1 →	Aerobic 2 →
NH_4^+ (mg-N/L)	11 ± 2.2	6.2 ± 1.2
NO_2^- (mg-N/L)	0.27 ± 0.00	0.31 ± 0.10
NO_3^- (mg-N/L)	1.9 ± 0.62	4.3 ± 1.3
DO (mg O_2/L)	1.7 ± 0.32	4.6 ± 0.82
Aqueous N_2O (μg/L)	58 ± 6.5	58 ± 5.1
Gaseous N_2O (ppmv)	3.0 ± 1.7	8.2 ± 4.5

Figure 4-8. Spatial Profile of Gaseous N_2O Concentrations and Typical Activated Sludge Variables in a Full-Scale Plug-Flow Process.
Results are from diurnal sampling over a period of 24 hours at each sampling point.
Arrows indicate wastewater flow. All zones were aerated.

Species	Aerobic 1 →	Aerobic 2 →
NH_4^+ (mg-N/L)	10 ± 0.99	6.2 ± 2.2
NO_2^- (mg-N/L)	0.27 ± 0.10	0.22 ± 0.00
NO_3^- (mg-N/L)	1.2 ± 0.42	2.7 ± 1.1
DO (mg O_2/L)	0.80 ± 0.47	1.8 ± 1.0
Aqueous N_2O (µg/L)	56 ± 9.8	62 ± 6.0
Gaseous N_2O (ppmv)	2.9 ± 0.73	51 ± 21

Figure 4-9. Spatial Profile of Gaseous N_2O Concentrations and Typical Activated Sludge Variables in a Full-Scale Plug-Flow Process.
Results are from diurnal sampling over a period of 24 hours at each sampling point. Arrows indicate wastewater flow. All zones were aerated.

Species	Influent →	Four-pass step-feed (covered tank, non-BNR) →	Effluent →
NH_4^+ (mg-N/L)	16 ± 4.2		7.0 ± 0.90
NO_2^- (mg-N/L)	0.10 ± 0.00		1.5 ± 0.69
NO_3^- (mg-N/L)	0.35 0.56		3.5 ± 1.3
N_2O (ppmv)		13 ± 13	

Figure 4-10. Spatial Profile of Gaseous N_2O Concentrations and Typical Influent and Effluent Variables in a Full-Scale Step-Feed (non-BNR) Activated Sludge Process. Results are from diurnal sampling over a period of 24 hours at each sampling point. Arrows indicate wastewater flow. All zones were aerated.

CHAPTER 5.0

RESULTS: MOLECULAR MECHANISMS OF AUTOTROPHIC N_2O AND NO GENERATION AND EMISSION

5.1 Impact of Anoxic Conditions on Nitrification by Nitrosomonas europaea 19718

The dominant mode of energy generation by AOB is via aerobic metabolic pathways (Chain et al., 2003) (un-shaded enzymes in Figure 5-1). However, under oxygen limiting and anoxic conditions, AOB including N. europaea, N. eutropha and several Nitrosospira spp. can utilize alternate electron acceptors such as NO_2^-, dimeric nitrogen dioxide (N_2O_4) and produce N_2O and NO, but not nitrogen gas (N_2) (Bock, 1995; Hooper et al., 1997; Schmidt and Bock, 1997; Schmidt and Bock, 1998) (enzymes shaded grey in Figure 5-1). The generation of N_2O and NO by chemolithoautotrophic AOB has been demonstrated widely and is predominantly attributed to nitrite reduction (Anderson and Levine, 1986; Sutka et al., 2006; Beaumont et al., 2002; Poth and Focht, 1985; Beaumont et al., 2004b; Ritchie and Nicholas, 1972; Kester et al., 1997; Jiang and Bakken, 1999; Shaw et al., 2006; Goreau et al., 1980; Wrage et al., 2004). While both NO and N_2O are produced under aerobic and microaerophilic conditions, only NO is produced under strict anoxic conditions (Kester et al., 1997; Ritchie and Nicholas, 1972), consistent with the results of this study. However, almost all previous pure-culture studies on N_2O and NO production by AOB have focused just on the transition from aerobic to anoxic conditions and the recovery back to aerobic conditions has not been well characterized. Additionally, information on the molecular mechanisms of N_2O and NO generation related to gene expression in response to abrupt transitions in metabolic activity (for instance, caused by anoxia) are relatively sparse. The significance of this part of the study lies in the correlation of responses at the gene transcription through whole-cell level of N_2O and NO generation by *N. europaea* cultures, when subject to cyclic transitions in DO concentrations. Such cycling can be encountered in engineered systems such as biological nitrogen removal wastewater treatment reactors, which are configured as sequential aerobic, anoxic or anaerobic reactors (Grady et al., 1999). Periodic cycling in ammonia and oxygen concentrations can also be prevalent and play a role in mediating autotrophic N_2O and NO emissions from soils (Wrage et al., 2004), which are especially enhanced after soil wetting events (Davidson et al., 1993).

5.2 Impact of Transient Anoxic Conditions on Whole-Cell Responses

At steady-state, the effluent NH_4^+ and NO_2^- concentrations were 2.2 ± 1.1 mg-N/L and 240 ± 41 mg-N/L, respectively. Cell concentrations were $2.4 \pm 0.52 * 10^8$ cells/ml with NH_4^+ oxidation associated sOUR values of $7.5 \pm 2.7 * 10^{-10}$ mg O_2/cell/min. Gaseous N_2O concentrations were not detectable and hence calculated liquid-phase N_2O concentrations were zero. Gaseous NO concentrations were 0.76 ± 0.026 ppm by volume and 21 ± 11% of the total cells contained intracellular NO.

The switch to anoxic conditions resulted in almost complete cessation of NH_4^+ oxidation (determined via mass balance, data not shown) and consequent NH_4^+ accumulation (Figure 5-2A). The level of NH_4^+ accumulation paralleled the influent NH_4^+ load during the anoxic phase (Figure 5-3B). Although imposition of transient anoxia resulted in a significant decrease in cell concentrations (Figure 5-2D), a substantial increase in the 'potential' NH_4^+ oxidation activity (measured as sOUR) was consistently observed towards the end of the anoxic phase, with subsequent reduction to steady-state levels (Figure 5-2D), when aeration was switched on again. The peak sOUR was nearly identical for all experiments conducted and did not vary with the level of NH_4^+ accumulation (data not shown).

As represented by Figure 5-2B, NO and N_2O generation were not coincident in response to transient anoxia. N_2O generation was primarily restricted to the recovery from anoxic to aerobic conditions. Peak N_2O emission consistently occurred just at the recovery from anoxic to aerobic conditions and correlated positively with the extent of NH_4^+ accumulation at the end of the anoxic phase. The ratio of ($q_{ns}/q_{max,ns}$) peaked at the same time as the gas phase N_2O concentrations but the magnitude of the ratio was irrespective of the peak N_2O concentrations themselves (Figure 5-3A). Calculated liquid phase N_2O contributed minimally to the overall nitrogen oxide inventory uniformly during all experiments, as represented by Figure 5-2C. Distinct from N_2O, NO was primarily generated during the anoxic phase and to a lesser extent during the recovery back to the aerobic phase. No systematic correlation was found between the amplitude of the NO peaks in either the anoxic or aerobic phases and the level of NH_4^+ accumulation (Figure 5-3B). The peak concentrations of NO and N_2O upon recovery to aerobic conditions were also not correlated, presumably since NO was being continuously converted to N_2O (Figures 5-3A through 5-B). The percentage of NO positive cells consistently increased to a peak during the anoxic phase during all experiments and decreased upon recovery to aerobic conditions (Figure 5-2D).

5.3 Impact of Transient Anoxia on Gene Expression

Of the four genes under consideration, *nirK*, which encodes for a copper containing nitrite reductase (Chain et al., 2003) was the most responsive gene to transient anoxic conditions (Figure 5.4). The expression of *nirK* increased upon transition to anoxia, but decreased to steady-state levels upon recovery to aerobic conditions. In direct contrast, the expression of *amoA, hao* and *norB* uniformly decreased during the anoxic phase. Irrespective of the extent of NH_4^+ accumulation during anoxia, the reduction in relative mRNA concentrations of *amoA* was the highest, followed by *norB* and *hao,* respectively, for all experiments conducted (Figure 5.4). Under the two higher levels of NH_4^+ accumulation tested, significant recovery within the anoxic period itself was observed for *hao* expression but not for *amoA* and *norB* expression. The time period of recovery for relative gene expression also correlated positively with the level of NH_4^+ accumulated during the anoxic phase. In general, reactor NH_4^+, $N_2O(l)$, $N_2O(g)$ and $NO(g)$ concentrations recovered to steady-state levels before the relative mRNA concentrations (Figures 5.2 through 5.4) suggesting that steady-state was reached faster at the metabolic level than at the gene transcription level.

5.4 Directionality in N_2O Generation

Based on the results of this study, a distinct directionality in N_2O generation by *N.*

europaea was demonstrated. Transition to anoxia itself did not result in N_2O generation, either in the absence of NH_4^+ (as occurring during the beginning of the oxygen limited period) or presence of NH_4^+ (as occurring at any given time during the anoxic period). Rather, it was the *recovery* from anoxia coupled with the *presence* of accumulated NH_4^+ and oxygen (both captured using Monod-type functions in Equation 5) that resulted in N_2O generation. In terms of biokinetics, it has been previously shown for chemoorganoheterotrophic denitrification that the rate of N_2O production from NO is a second order function of NO concentrations (Girsch and de Vries, 1997). In contrast, the rate of autotrophic N_2O production in this study varied not as a function of NO concentrations, but as a function of NH_4^+ accumulation during the anoxic phase (Figure 5.3A-B). A similar positive correlation between NO generation and transient spikes of NH_4^+ has also been recently reported by mixed nitrifying cultures (Kampschreur et al., 2008a). The lack of N_2O production (via reduction of NO) during the anoxic phase possibly resulted in the observed sole accumulation of NO (Figure 5.2B). The generation of NO during anoxia accompanied by concurrent higher expression of *nirK* pointed to a well established anoxic metabolism in *N. europaea*, whereby NO_2^- could be used as a terminal electron acceptor with hydroxylamine (NH_2OH) or internal reducing equivalents acting as possible electron donors. Reduction of NO concentrations after the initial peak during the anoxic phase point to the depletion of electron donors or decreased activity of reactions producing these donors (for instance, NH_2OH oxidation as modeled recently (Chandran and Smets, 2008)).

5.5 Mechanisms of Autotrophic Responses to Transient Anoxia

The time-response of changes in expression of the four genes demonstrated the high rapidity with which *N. europaea* exhibited a coordinated response to anoxic conditions. This response enables utilization of NO_2^- as an alternate electron acceptor accompanied by a reduction in the expression of other pathways (such as NH_4^+ oxidation and NO reduction), presumably to conserve energy and cellular resources. Additionally, the slow recovery of mRNA levels compared to recovery in N-species concentrations (indicating metabolic-level recovery) points to a possible mechanism to counter repeated oxygen transients. A similar behavior in selective *amoA* mRNA retention by *N. europaea* and other AOB to address transient NH_4^+ starvation and sufficiency has been described previously (Bollmann et al., 2002). Additionally, the occurrence of N_2O generation before recovery in *norB* mRNA concentrations upon return to aerobic conditions also suggests that N_2O generation was governed more at the enzyme activity and metabolic levels rather than solely at the gene transcription level.

The relative expression patterns of four genes involved in nitrogen transformations in *N. europaea* also suggest differential regulation thereof in response to transient anoxia. The presence of high nitrite concentrations (~20 mM) may have resulted in the strong response of *nirK* during the transition into DO limitation (Figure 6.4). It has indeed been shown previously that NO (and in turn N_2O) generation by co-cultures of *N. europaea* and *Nitrobacter winogradskyi,* (which consequently resulted in low NO_2^-- culture concentrations), was lower than by pure cultures of *N. europaea* (Kester et al., 1997). The increase in *nirK* expression under anoxic conditions reflected negative control of NO_2^- reduction by oxygen concentrations and once again, possible use of NO_2^- by *N. europaea* as an electron acceptor, which was eventually diminished upon return to aerobic conditions. On the other hand, the mutually distinct transcription and expression of *nirK* and *norB* in *N. europaea* is in contrast to the parallel expression of these two genes in chemoorganoheterotrophic denitrification (Zumft, 1997).

Although the specific reason for a more rapid recovery in *hao* relative mRNA levels cannot be conclusively determined from the data obtained in this study, it maybe speculated that either the accumulating NH_4^+ concentrations during anoxia or the postulated supporting role of HAO in nitrite reduction (Kester et al., 1997) may have contributed to this observation. The reduced *hao* recovery at the lowest NH_4^+ accumulation also points to possible control of *hao* expression by NH_4^+ concentrations under transient anoxic conditions. The differing expression patterns of *amoA* and *hao* are also singular given the well-established electron based coupling between the AMO and HAO (Chandran and Smets, 2008; Hooper, 1969 (b)). Therefore, in both oxidative (*amoA* and *hao*) and reductive (*nirK* and *norB*) metabolism of *N. europaea*, transcription of enzymatically sequential pathways followed independent directions, indicating a high degree of flexibility and versatility in overall energy transduction of *N. europaea.*

5.6 N_2O and NO as Indicators of Metabolic Activity in N. europaea

The coincident peaking of sOUR, ($q_{ns}/q_{max,ns}$) and N_2O(g) concentrations (Figure 5-3A) point to a link between N_2O production with periods of high specific activity (q_{max}) or alternately high metabolic rates during periods of high nitrogen flux through the catabolic pathways. This link is underscored by the significantly lower production of N_2O and NO under steady-state operation with correspondingly lower effluent NH_4^+ concentrations and consequently $q<<q_{max}$. Given that N_2O generation is associated with a transition from low levels of specific activity ($q<q_{max}$) towards higher levels (q_{max}), one strategy to minimize N_2O emissions from nitrifying wastewater treatment plants could be to minimize transient build-up of NH_4^+-N especially at the interface from the anoxic to the aerobic zones. Indeed, positive correlation between the actual specific ammonium oxidation rate and N_2O emission as observed in this study has recently been used as the basis to propose the use of N_2O emissions as an indicator of nitrification process upsets (Burgess et al., 2002; Butler et al., 2009).

From an engineering perspective, it is essential for operators of wastewater treatment reactors to be able to predict N_2O emission by nitrification (and denitrification), as the wastewater industry makes a concerted effort to sustainably address both *aqueous* and *gaseous* nitrogen pollution. From this standpoint, the formulation of operational parameters such as the ratio of ($q_{ns}/q_{max,ns}$) may be significant from both a process perspective and a fundamental understanding of N_2O generation by AOB in wastewater treatment reactors. Based on full-scale measurement campaigns, as described in Chapter 4.0 and in (Ahn et al., 2009), N_2O emissions from nitrifying wastewater treatment plants are restricted mainly to the transition from the anoxic to aerobic zones or to regions of high NH_4^+ and oxygen concentrations (which lead to high q_{ns} values). Therefore, N_2O emissions from these plants appear to be associated with *recovery* from oxygen limitation or alternately to regions of high $q_{ns}/q_{max,ns}$, precisely as demonstrated by the results of this study. By extension, process configurations that operate under consistent q_{ns} values (such as oxidation ditches with uniform DO concentrations) are expected to produce less N_2O than those that subject AOB to frequent transitions in q_{ns} (such as sequencing batch or pre-denitrification processes such as Modified Lüdzack Ettinger).

5.7 Conclusions

Based on the results obtained, our initial hypotheses on the triggers of gene expression and N_2O and NO production by *N. europaea* were rejected. The results implicate *recovery* from abrupt transient anoxia rather than *imposition* thereof, in the generation and emission of N_2O by chemostat cultures of *N. europaea* – under concomitant NH_4^+ accumulation. In contrast, NO emission is primarily due to *imposition* of anoxia. The gaseous emissions have distinct underpinnings in rapid changes at the gene expression and metabolic levels and can be correlated to changes in specific AOB activity.

From a more practical perspective, in the mixed-communities of BNR activated sludge, both nitrification and denitrification can contribute to overall N_2O production. Constant cycling between anoxic and aerobic conditions in BNR reactors are expected to promote N_2O emissions from not only denitrification (owing to O_2 mediated inhibition), especially in the presence of residual organic carbon and nitrate, but also from nitrification, owing to the directional behavior of AOB metabolism, as discussed in this chapter. A big gap existing in our knowledge of N_2O emissions from WWTPs is the relative contribution of nitrification and denitrification. Building upon the mechanisms of autotrophic N_2O generation presented in this chapter and factors promoting denitrification related N_2O emissions (presented next), in combination with ^{15}N isotopic studies, it might become possible to overcome this knowledge gap in future research.

Table 5-1. Endpoint and Real-Time PCR Primers Employed in this Study.
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Primer	Sequence (5'-3')	Position	Target gene	Reference
	Endpoint PCR			
A189	GGHGACTGGGAYTTCTGG	151-168	*amoA*	(Holmes et al., 1995, Okano et al., 2004)
amoA2R'	CCTCKGSAAAGCCTTCTTC	802-820		
HAO1F	TCAACATAGGCACGGTTCATCGGA	203-226	*hao*	This study
HAO1R	ATTTGCCGAACGTGAATCGGAACG	1082-1105		
NirK1F	TGCTTCCGGATCAGCGTCATTAGT	31-54	*nirK*	This study
NirK1R	AGTTGAAACCGATGTGGCCTACGA	809-832		
NorB1F	CGGCACTGATGTTCCTGTTTGCTT	479-502	*norB*	This study
NorB1R	AGCAACCGCATCCAGTAGAACAGA	1215-1238		
KNO50F	TNANACATGCAAGTCGAICG	49-68	Eubacterial 16S rRNA gene	(Moyer et al., 1994)
KNO51R	GGYTACCTTGTTACGACTT	1492-1510		
	Quantitative PCR			
amoAFq	GGACTTCACGCTGTATCTG	408-426	*amoA*	(Chandran and Love, 2008)
amoARq	GTGCCTTCTACAACGATTGG	524-543		
HAO1Fq	TGAGCCAGTCCAACGTGCAT	266-285	*hao*	This study
HAO1Rq	AAGGCAACAACCCTGCCTCA	331-350		
NirK1Fq	TGCAGGGCATACTGGACGTT	182-201	*nirK*	This study
NirK1Rq	AGGTGAACGGGTGCGCATTT	291-310		
NorB1Fq	ACACAAATCACTGCCGCCCA	958-977	*norB*	This study
NorB1Rq	TGCAGTACACCGGCAAAGGT	1138-1157		
EUBF	TCCTACGGGAGGCAGCAGT	339-357	Eubacterial 16S rRNA gene	(Nadkarni et al., 2002)
EUBR	GGACTACCAGGGTATCTAATCCTGTT	780-805		

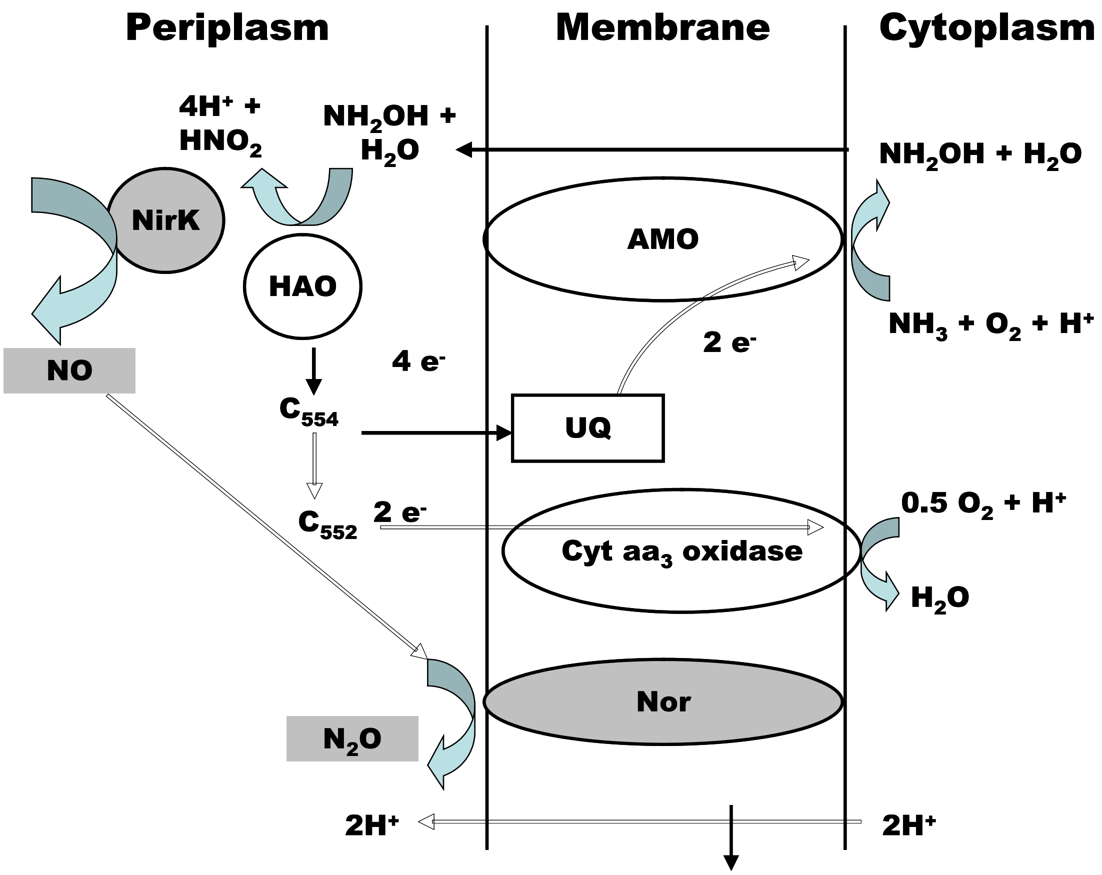

Figure 5-1. Electron Transport Pathway in *N. europaea*.
Unshaded enzymes (AMO and HAO) represent nitrogen oxidation pathways and shaded enzymes (NirK and Nor) represent nitrogen reduction pathways (after (Hooper et al., 1997))

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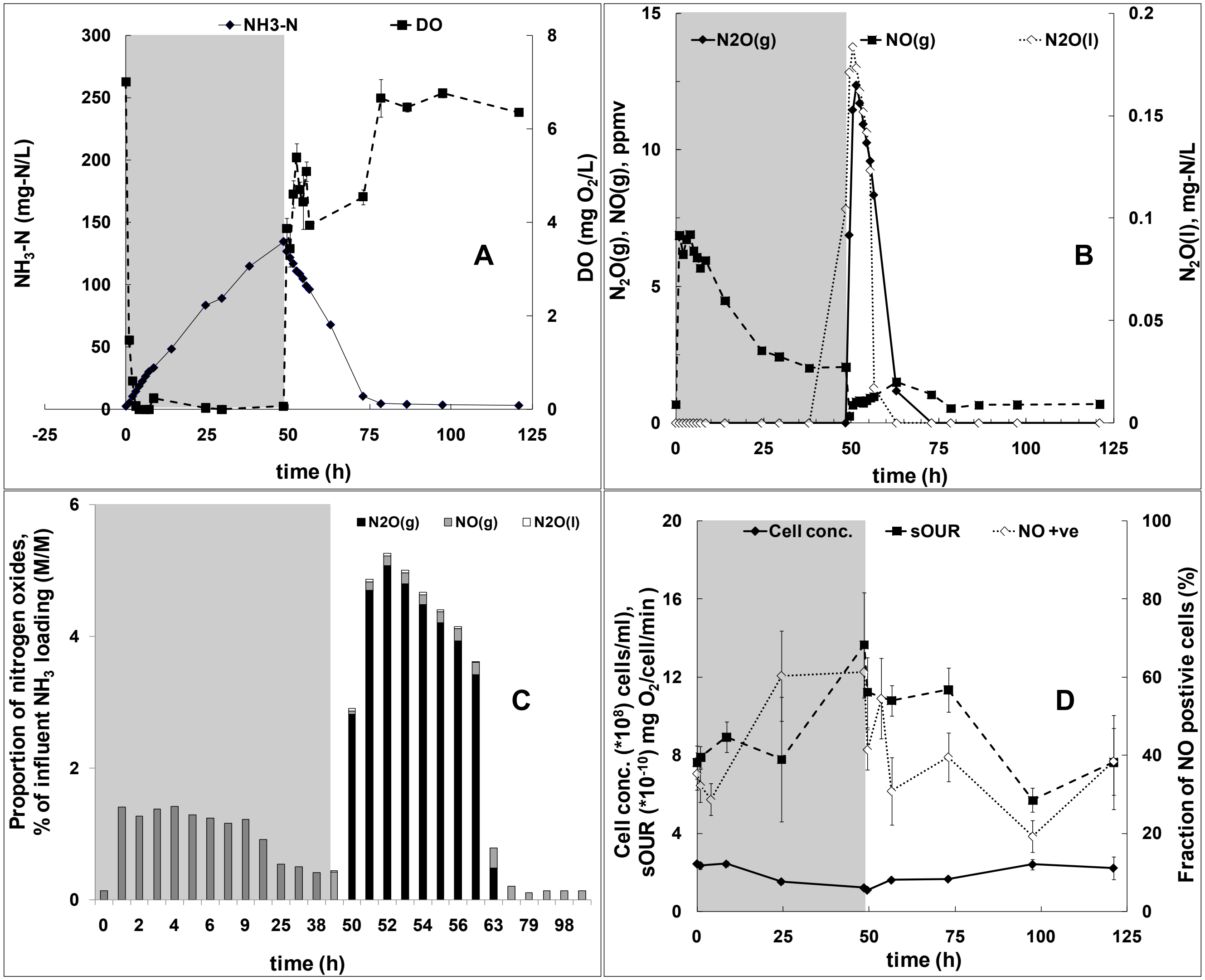

Figure 5-2. Impact of Transient Oxygen Limitation (shown in gray) on NH$_4^+$ Accumulation (A), Gaseous N$_2$O, Gaseous NO and Calculated Liquid N$_2$O (B), Relative Proportion of Influent NH$_4^+$ Converted to Gaseous N$_2$O, Gaseous NO and Liquid N$_2$O (C) and Cell Concentrations, Specific Oxygen Uptake Rate and Proportion of Cells with Intracellular NO (D). Reprinted with permission from *Environmental Science and Technology*, 2010, American Chemical Society.

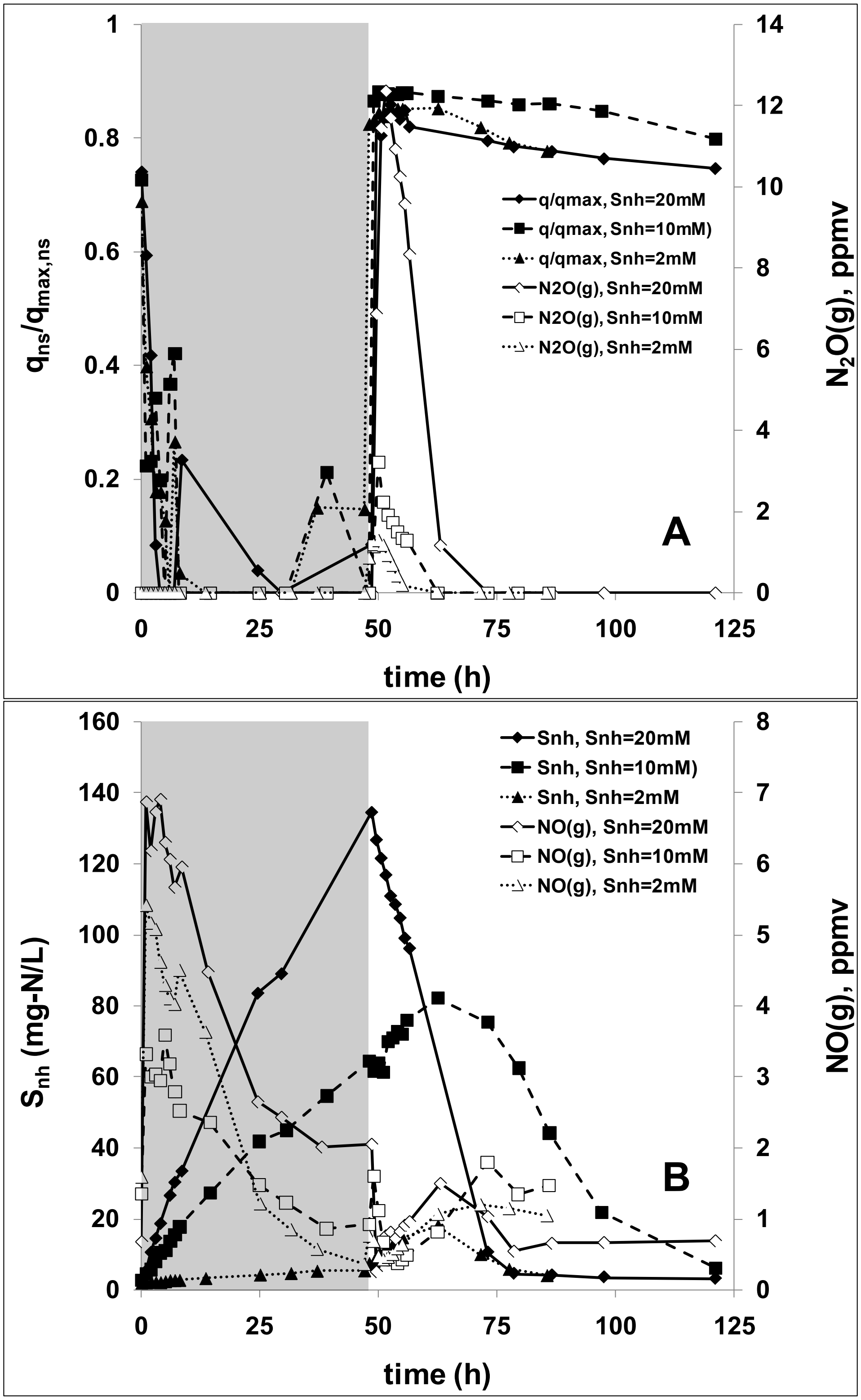

Figure 5-3. Concurrent Peaking of $q_{ns}/q_{max,ns}$ and Gaseous N_2O Concentrations Upon Recovery to Aerobic Conditions for Three Different Influent NH_4^+ Concentrations (A), Corresponding Profiles of NH_4^+ and NO Concentrations during the Same Experiments (B).

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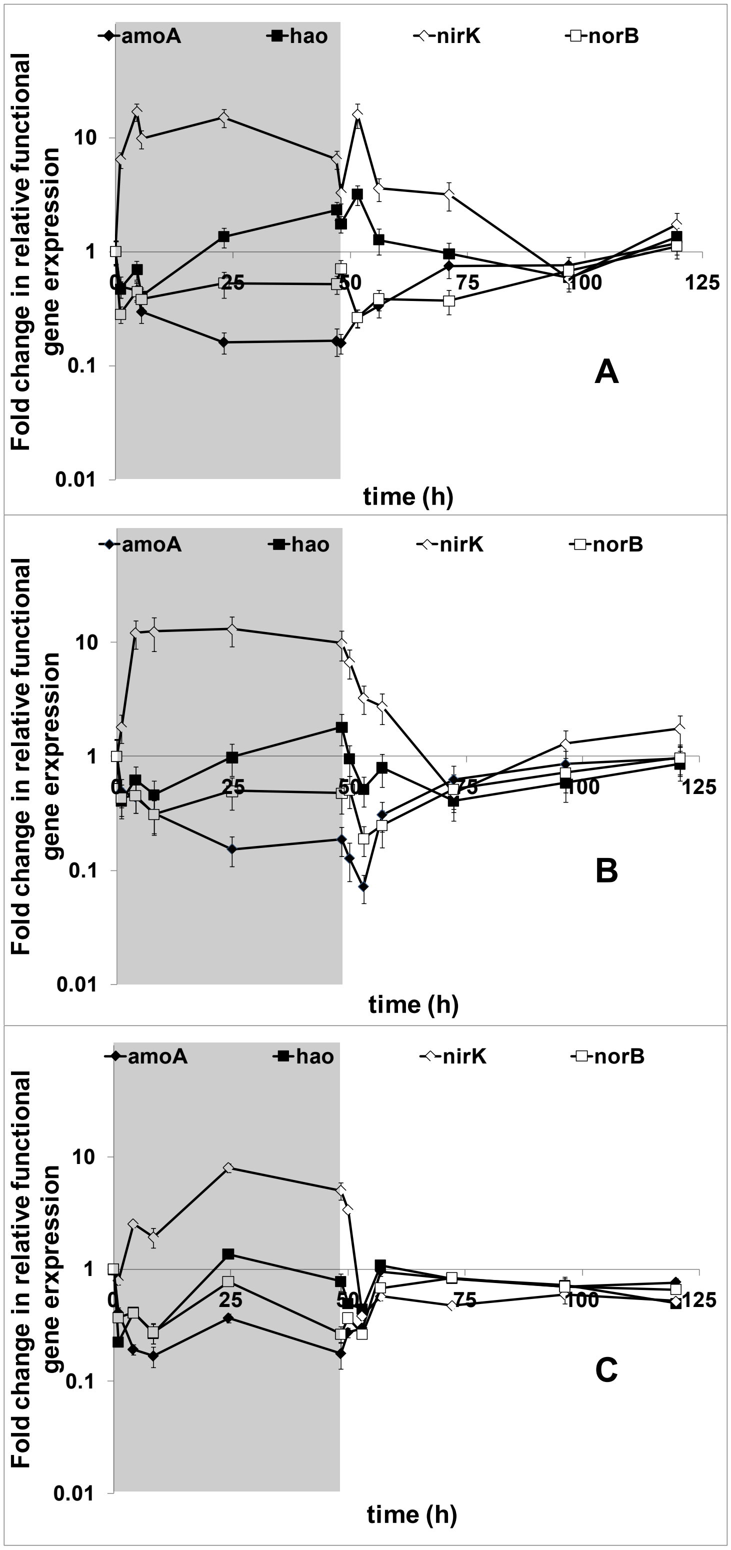

Figure 5-4. Impact of Transient Oxygen Limitation On Select Functional Gene Expression Profiles in *N. europaea* with 20mM (A), 10mM (B) and 2mM (C) Influent NH_4^+ Concentrations during Oxygen Limitation. Influent NH_4^+ Concentrations before and after the Transition Period were 20mM.

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CHAPTER 6.0

RESULTS: FACTORS PROMOTING EMISSIONS OF NITROUS OXIDE AND NITRIC OXIDE FROM DENITRIFYING SEQUENCING BATCH REACTORS OPERATED WITH METHANOL AND ETHANOL AS ELECTRON DONORS

6.1 Steady State Performance and Emissions of N_2O and NO during Denitrification using Methanol and Ethanol as Electron Donors

During steady-state operation, near complete nitrate removal was observed in both SBRs (methanol: 92.5 ± 11.6 %, ethanol: 98.5 ± 2.5 %) with minimal nitrite accumulation (<1 mg-N/L). Little N_2O (methanol: 0.1 ± 0.02 %, ethanol: 0.1 ± 0.01 %) or NO (methanol: 0.04 ± 0.01%, ethanol: 0.01 ± 0.00%) was emitted (Figure 1a and 1b). In keeping with the sequential production of the two species during denitrification, NO concentrations peaked before N_2O concentrations during any given SBR cycle (Figures 6a(1) and b(1)).

Under steady-state operation, factors leading to incomplete denitrification have generally been attributed to N_2O production. For instance, in a recent study, complete denitrification resulted in 0.1% of the removed nitrate emitted as N_2O. In contrast, the extent of emissions was substantially higher (1.3%) as nitrate removal dropped to 66% (Tallec et al., 2006). These results are consistent with the low steady-state N_2O and NO emissions from both SBRs, wherein nitrate removals higher than 90% were observed without concomitant nitrite accumulation. The fraction of influent nitrate removed that was emitted as N_2O for methanol (0.12%) was comparable with previous results in the range of 0.2-1.3% with methanol (Park et al., 2000). Emissions with ethanol enriched denitrifying bacteria have not been reported previously and thus cannot be directly compared.

6.2 Impact of Transient Carbon Limitation

Transient carbon limitation resulted in transient nitrate accumulation for both methanol and ethanol fed SBRs. Relatively lower nitrate accumulation was observed during ethanol limitation than during methanol limitation (data not shown), which can be explained by faster denitrification biokinetics for ethanol than methanol (Baytshtok et al., 2009). Nitrite accumulation was similar for both COD sources and much lower than nitrate accumulation (data not shown). However, owing to the long react phase and the operating SRT of 10 days, complete nitrate removal was eventually observed by the end of the overall cycle for both reactors. N_2O and NO emissions during a cycle were statistically lower than steady state control for the methanol fed SBR, but were largely similar in the ethanol fed SBR (Figures 6-1a and b).

The lack of significant N_2O emissions during carbon limitation are in contrast to some previous reports. It has been postulated that the higher electron affinities of two upstream denitrification enzymes, NaR and NiR, relative to downstream NOR and N_2OR enzymes could be the reason for N_2O accumulation during carbon limitation (Betlach and Tiedje, 1981; Knowles, 1982). While specific enzyme affinities were not directly measured in this study, it is possible that the distinct populations fostered by methanol and ethanol (as described previously Baytshtok et al., 2009) might possess more uniform and high affinities across the sequential reductive nitrogen cascade, leading to the lack of N_2O and NO emissions during carbon limitation.

The possession of high affinities could be due to the high operating SRT of the SBRs for over two years, which could have resulted in long-term enzymatic adaptation to low substrate (carbon and nitrate) concentrations. Indeed, minimal N_2O emissions were observed from acetate-limited denitrifying reactors operated at high SRT values (10 days) (Hanaki et al., 1992). Additionally, adaptation of *Alcaligenes faecalis* cultures to cycling between feast and famine resulting in lower N_2O production has also been shown (Otte et al., 1996). Therefore, these results show that the link between carbon limitation and N_2O emission may not be universal for all carbon sources and operating conditions, and needs to be evaluated more specifically.

6.3 Impact of Nitrite Inhibition

Exposure to nitrite led to statistically higher nitrate accumulation at the end of the SBR cycle for both carbon sources, indicating feedback inhibition of nitrate reduction by nitrite (data not shown). However, near complete nitrite reduction was still achieved in the ethanol fed SBR, but not in the methanol fed SBR (76.5 ± 3.2 %). The nitrite transient also resulted in a slightly elevated secondary peak of NO (Figure 2a(3) and 2b(3)) compared to steady-state (Figure 6-2a(1) and 6-2b(1)) for both SBRs. Nevertheless, N_2O emissions were not impacted and the resulting fractions of nitrate converted to N_2O and NO were statistically similar (at the α=0.05 confidence level) to those at steady state (Figure 6-1a).

It has been previously suggested that N_2OR is more sensitive to nitrite inhibition compared to other enzymes in denitrification, thus leading to N_2O production under nitrite exposure (Knowles, 1982). Besides the direct impact of nitrite, N_2OR inhibition can also be due to NO, which is formed from nitrite reduction (Goretski et al., 1990). Indeed, accumulation of N_2O and NO during denitrification in the presence of nitrite was observed with acetate and yeast extract fed denitrifying cultures, with an inhibitory threshold nitrite concentration of approximately 10 mg-N/L (Hanaki et al., 1992; von Schultess et al., 1995). However, at the same nitrite concentration, little N_2O production was observed from activated sludge with sucrose as sole carbon source. Another study using pure cultures of *Alcaligenes sp.* and *P. fluorescens* grown on nutrient broth as carbon source also reported no impact of nitrite pulses on N_2O accumulation (Betlach and Tiedje, 1981). The differences in N_2O production as a function of nitrite exposure in these different studies possibly could be due to the different carbon sources used or the mode of cultivation used. Therefore, the previous results and this study essentially underscore the lack of generality in the link between nitrite exposure and N_2O production, from denitrification using different carbon sources.

6.4 Impact of Oxygen Inhibition

In both methanol and ethanol fed SBRs, a rapid initial accumulation of nitrate was observed upon the introduction of air or oxygen (Figure 6-3). Higher inhibition of oxygen on nitrate reduction occurred in the methanol fed SBR. In contrast, a higher (but delayed) nitrate removal occurred in the ethanol fed SBR at all DO concentrations. As expected, there was a positive correlation between DO concentration and the extent of nitrate accumulation for both carbon sources. High nitrite accumulation was also observed in both SBRs, but was more pronounced in the ethanol fed SBR due to ongoing nitrate reduction therein. N_2O emission was statistically higher than the control in the ethanol fed SBR (Figures 6-4b through d) and the highest emissions were at DO = 9.0 mg/L, where as much as 7.1% of influent nitrate load was emitted as N_2O (Figure 6-1b). NO emissions were much lower, but displayed a similar positive correlation with increasing DO concentrations. In contrast, methylotrophic denitrification did not result in significant N_2O or NO emissions at any DO concentration tested (Figure 6-3a).

The relative production of N_2O by the two SBRs could not be entirely described by a reduction in their specific nitrate depletion sDNR values (Figure 6-5). Though the sDNR values for the ethanol SBR were consistently higher than those for the methanol SBR, the extent of reduction due to oxygen inhibition was statistically similar (at the α=0.05 confidence level) and not in correspondence with much higher N_2O production from the former (Figure 6-4). The inability of nitrate sDNR values to describe the extent of N_2O emissions is expected and can be attributed to inhibition of not just NaR but also the other nitrogen reductases by oxygen.

It is reported that N_2OR is more sensitive to oxygen inhibition than the remaining upstream nitrogen reductase enzymes, thus leading to selective N_2O production (Knowles, 1982; Korner and Zumft, 1989). Based on the results of this study, differential N_2O production could also be related to differential NaR inhibition by oxygen. In the methanol-fed SBR, complete cessation of nitrate reduction occurred at the highest oxygen concentration tested (Figure 6-3a(3)). Therefore, the lower level of nitrite, N_2O or NO production in the methanol-fed SBR was in fact mainly due to less upstream nitrate reduced than in the ethanol-fed SBR (Figure 6-3a). It should be pointed out that downstream nitrogen reductases (NOR and N_2OR enzymes) could also have been inhibited in the methanol-fed SBR, but this could not be discerned due to the lack of accumulation of their substrates. On the other hand, the NaR system in the ethanol fed SBR was seemingly more robust, as reflected in near-complete albeit delayed nitrate reduction (Figure 6-3b). However, such ongoing nitrate reduction under oxygen inhibiting conditions resulted in N_2O production.

6.5 Conclusions

This study emphasizes that N_2O and NO emissions from denitrification cannot be generalized for all carbon sources, and must be addressed on a case-specific basis. Based on the differences observed, specific mechanisms and pathways of N_2O and NO production on different carbon sources also need to be elucidated. Additionally, dosing of ethanol to anoxic zones in BNR processes might need to be strictly controlled not only to minimize ethanol wastage but also to minimize the generation and emission of N_2O in downstream aerobic zones.

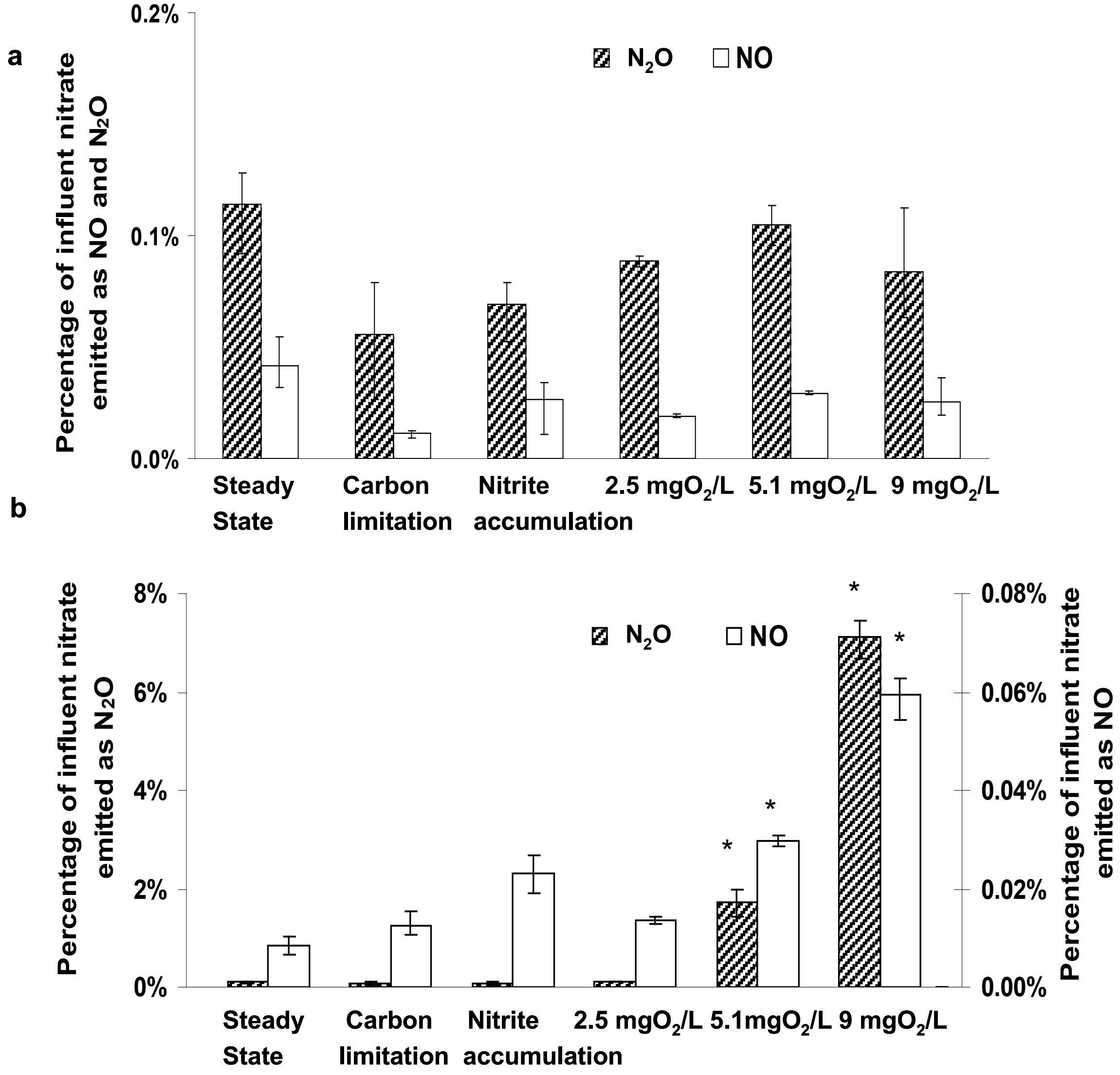

Figure 6-1. Fraction of Influent Nitrate Load Emitted as N_2O and NO in (a) Methanol Fed SBR and (b) Ethanol Fed SBR Under Steady State, Carbon Limitation, Nitrite and DO Inhibition.

* indicates results significantly different from steady-state at $\alpha = 0.05$.

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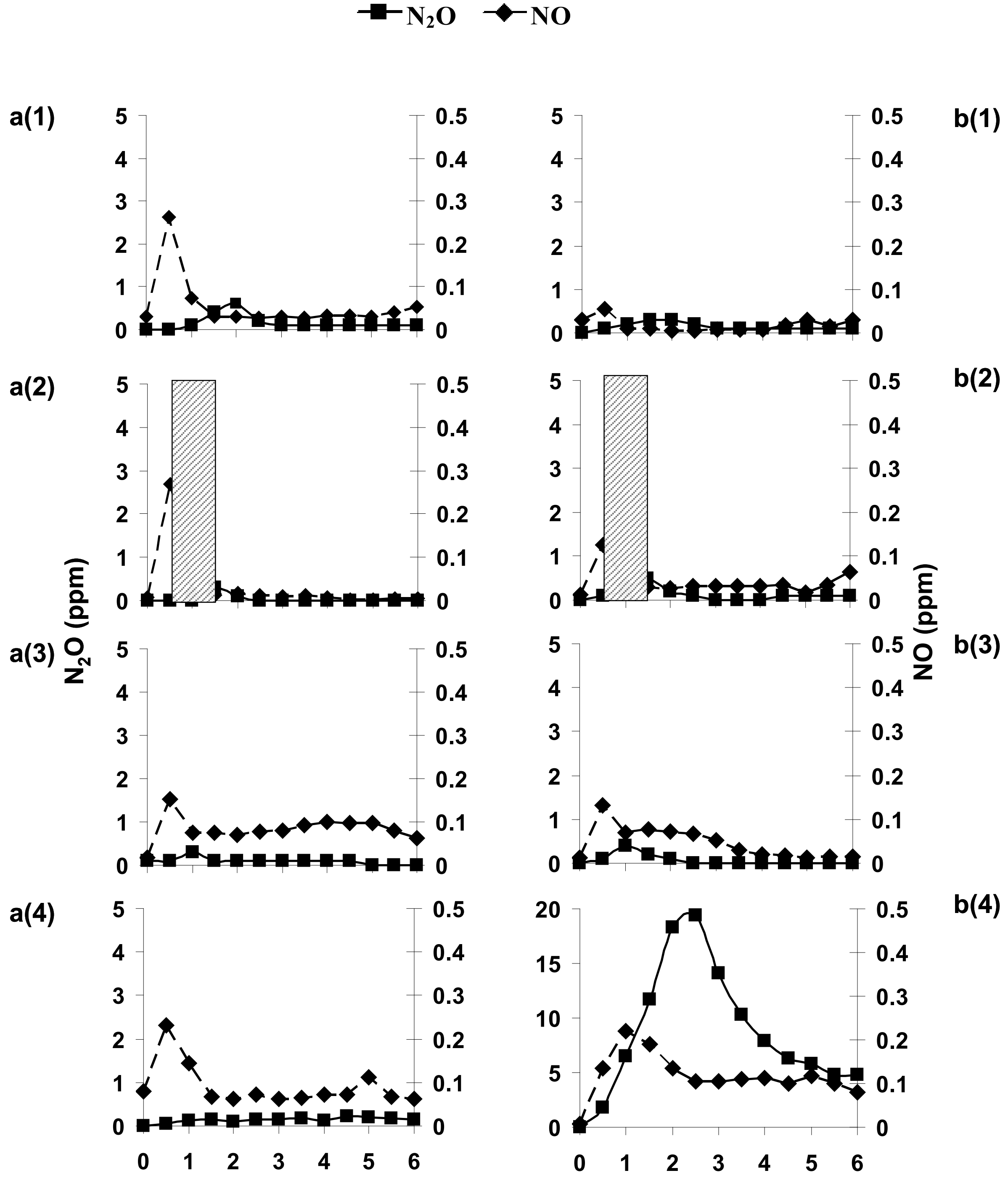

Figure 6-2. Representative N_2O (primary axis) and NO (secondary axis) Emissions from (a) Methanol Fed SBR and (b) Ethanol Fed SBR Under Steady State (1), Carbon Limitation, Shaded Box (2), Nitrite Inhibition (3), and DO Inhibition at 9.0 mg O_2 /L (4).

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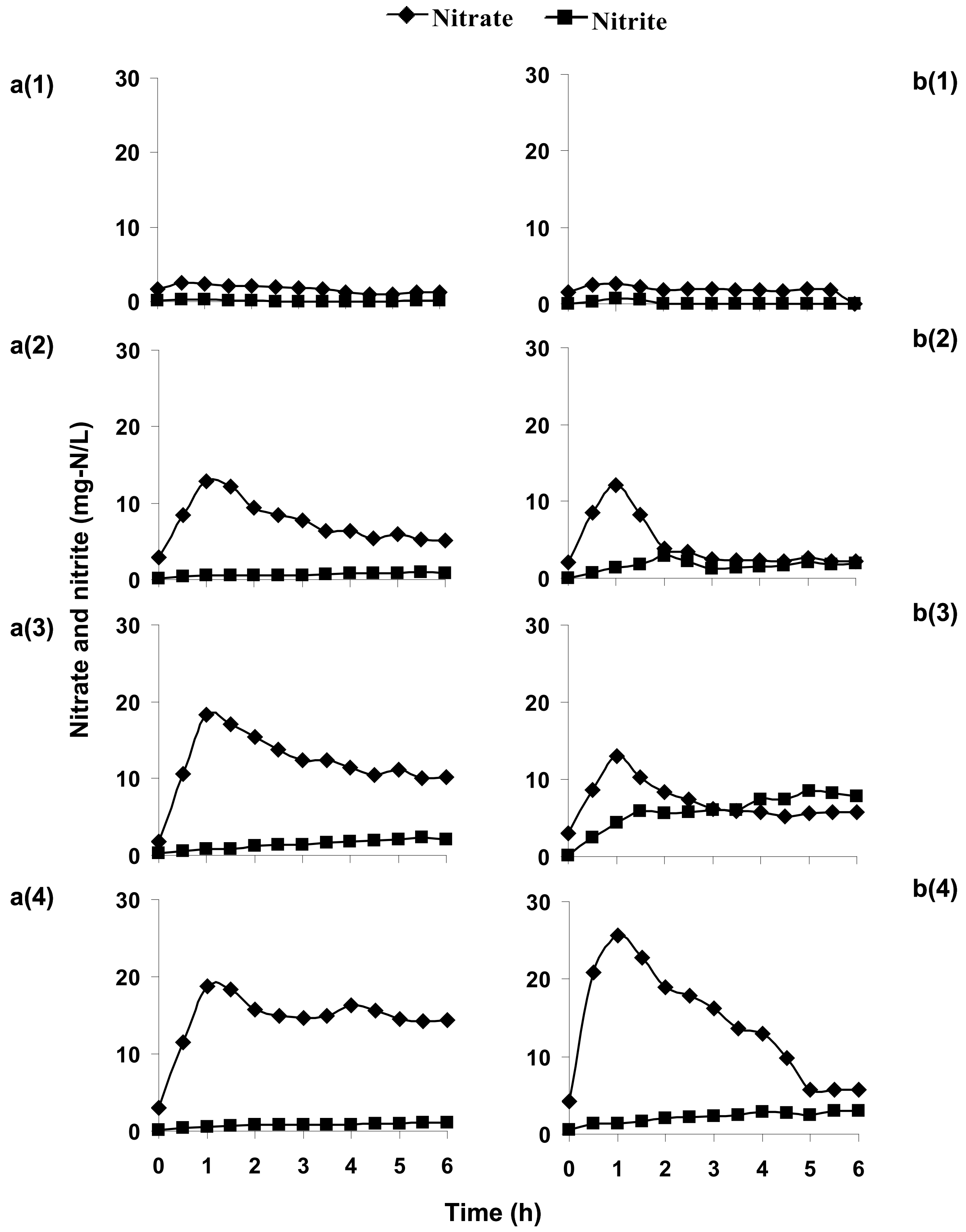

Figure 6-3. Representative Nitrate and Nitrite Concentrations from (a) Methanol Fed SBR and (b) Ethanol Fed SBR Under Steady-State (1) and Different DO Concentrations (2)-(4): DO=2.5, 5.1 and 9.0 mg/L Respectively. The SBR cycle phases were the same as shown in Figure 7-2.

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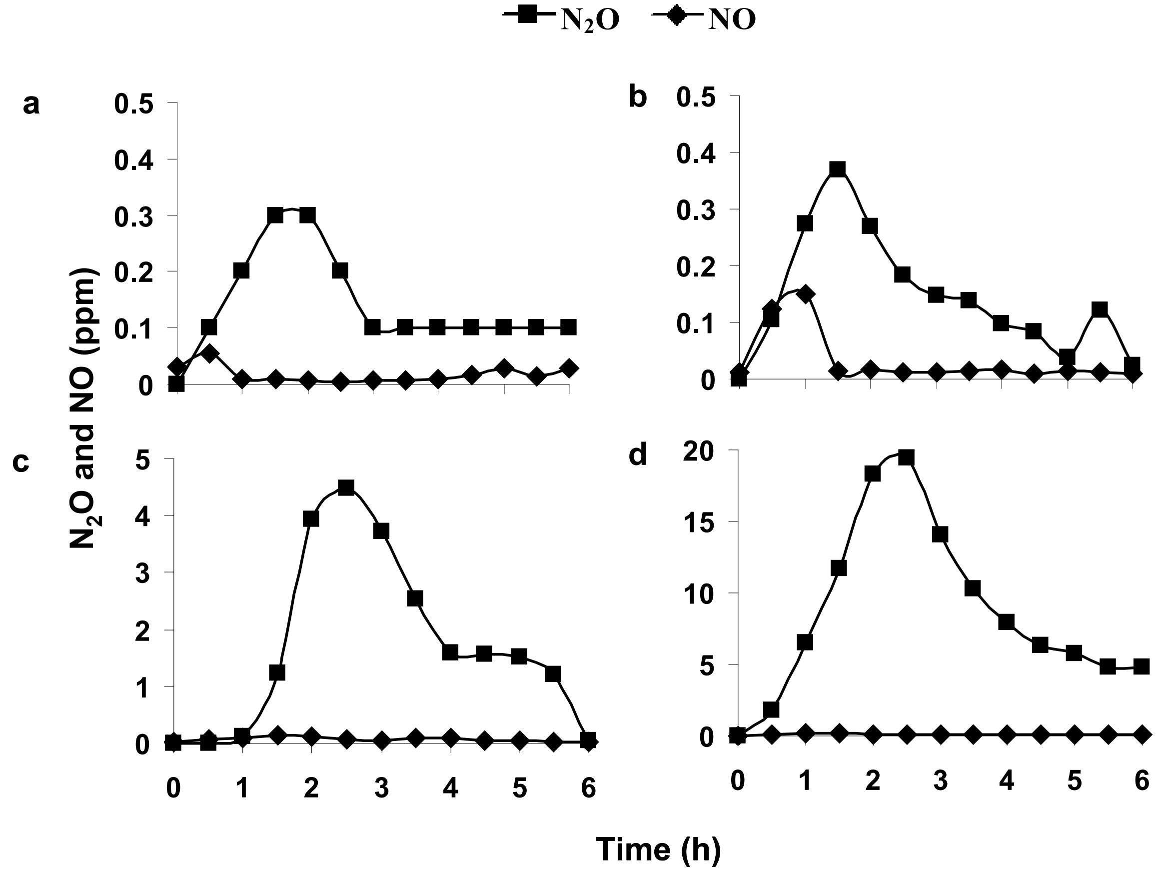

Figure 6-4. N_2O and NO Emissions from Ethanol Fed SBR Under Steady State (a) and Different DO Concentrations (b-d: DO=2.5, 5.1 and 9.0 mg/L Respectively).
The corresponding nitrate and nitrite profiles are shown in Figure 7-3-b-1 through 7-3-b-4.
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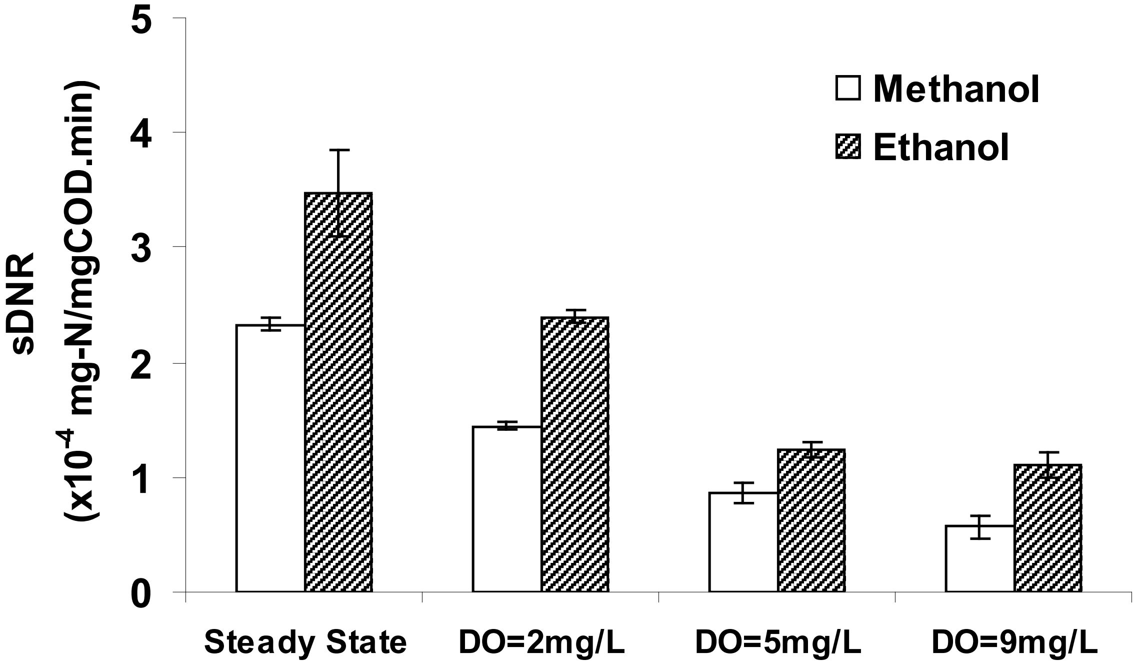

Figure 6-5. Impact of DO Concentrations on Biokinetics of Methanol- and Ethanol-Based Denitrification.
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CHAPTER 7.0

INTERIM CONCLUSIONS, RECOMMENDATIONS, AND ONGOING STUDIES

7.1 N_2O Emissions from Different WWTP Configurations

The results from this study are important since they involve the first systematic measurement of N_2O inventories from wastewater treatment processes in the United States with a wide range of process configurations and operating conditions. Based on the results of this study, it should be noted that wastewater plants are not expected to be prime contributors to overall N_2O fluxes. In the absence of this study, there would continue to be lingering uncertainties regarding the magnitude of N_2O emission fluxes from wastewater treatment facilities, owing to the limitations of the currently followed 'estimation' approach. Indeed, some studies in the Netherlands and Germany have implicated WWTPs to be far more significant contributors to N_2O emissions than that found in this work. Specifically, N_2O emissions as high as 7-15% of the TKN load processed have been reported in these previous studies(Kampschreur et al., 2008b; Wicht and Beier, 1995). Such uncertainty could lead to unrealistic regulatory mandates for both *aqueous* and *gaseous* N-discharges from WWTPs. This would be unnecessarily burdensome on WWTPs, some of which are already strained to meet increasingly lower nutrient removal mandates. Therefore, the authors feel that this work represents a significant extension to scientific knowledge in the direction of greenhouse gas emissions from WWTPs.

7.2 Estimation of N_2O Emission Factors

This study has considerably expanded the database of N_2O emissions obtained from WWTPs (as summarized in Chapter 4.0, Table 4-4). Notably, the information on N_2O emissions obtained in this study has been predominantly using online measurements. These are necessitated because of the continuously changing emissions, resulting from the dynamic response of nitrifying and denitrifying bacteria to changing influent loads and process conditions (such as DO and local N-species concentrations). Therefore, this study is a big improvement over previous ones that relied on spatially localized or discrete measurements of N_2O concentration measurements or discontinuous (grab-sample based) N_2O emissions measurements. As this study and other studies worldwide expand to even more BNR and non-BNR configurations, it is expected that the range of emissions and emission factor estimates will evolve and improve considerably.

7.3 N_2O Emissions from Different WWTP Configurations

When compared to previous such full-scale studies in Europe and Japan, the range of N_2O emissions observed in this study is relatively smaller, falling mostly in the range 0.03 – 0.60% (Table 4.IV). The only other study in the United States was from a single non-BNR facility in Durham, NH and reported that 0.035 % of the influent TKN load was emitted as N_2O

(Czepiel et al., 1995). The emissions measured in the present study, which are all from activated sludge reactors treating primary effluent are notably lower than those in separate anaerobic digestion reject water treatment measured recently in the Netherlands (Kampschreur et al., 2008b). Additional processes/configurations yet to be sampled are expected to provide more information on the relative range of N_2O emissions. Based on full-scale data gathered to date and lab-scale observations, it is expected that the specific sequence of anoxic- and aerobic- zones and the extent of loading to a process govern the overall N_2O emissions from a given activated sludge process. Since the configurations and loadings were widely different (Table 4-1), no generalizations can be made at this point regarding the efficacy of one process configuration over another in limiting N_2O emissions.

A specific correlation between operating temperature and N_2O emissions cannot be inferred at this stage. Additional sampling campaigns at different temperatures are being conducted at each WWTP to determine the impact of temperature on measured N_2O emissions.

7.4 Implications of Variability in N_2O Emissions on Inventory Calculations

Given the substantial spatial and diurnal variability and the broad range of emission fractions obtained from the different WWTPs in this study, the concept of a ‘single lumped’ emission factor to describe dynamic nitrification or denitrification related N_2O generation and emission, as followed by the U.S. EPA and the IPCC, is inadequate. Normalization of emission factors to wastewater flow rate may not be appropriate owing to different global water use patterns (Tchobanoglous et al., 2003) or to internally generated high-strength, low flow rate reject water or centrate streams. Additionally, given the high degree of spatial and temporal variability of measured N_2O emissions, the development, calibration and validation of dynamic mechanistic process models that capture such variability would be more appropriate.

7.5 Mechanisms of N_2O Emissions by Nitrification and Denitrification

Based on the lab-scale studies presented in Chapter 4.0 and 5.0, new insights have been developed into the mechanisms of N_2O emissions specifically from nitrification and from denitrification using different external electron donors. From the viewpoint of nitrification, the predominant factors implicated in N_2O production have been oxygen limitation or anoxia and high nitrite concentrations (as discussed in (Yu et al., 2010)). Based on recent results ((Yu et al., 2010) and shown in Chapter 4.0), N_2O generation from nitrification can also occur under completely aerobic conditions, in the presence of non-limiting NH_4^+-N and DO concentrations. Although not conclusively proven at full-scale, this mechanism could be potentially involved in N_2O emissions observed just at the transition between primary anoxic zones and aerobic zones or at the effluent end of plug-flow systems in the presence of non-limiting NH_4^+-N and DO concentrations (as discussed in Chapter 4.0).

As discussed in (Lu and Chandran, 2010) and in Chapter 6.0, the type of external carbon source used for denitrification can also have an impact on N_2O and NO emissions. In a direct comparison between methanol and ethanol, N_2O emissions from the latter were statistically higher during oxygen mediation denitrification inhibition. Therefore, from a practical perspective, it is important for anoxic zones to be adequately sized to minimize the break-through of the electron donor (like ethanol) and nitrate into succeeding aerobic zones and consequently production of N_2O and NO.

7.6 N_2O Emissions from WWTPs and Sustainable BNR Design and Operations

The sustainable management of nitrogenous pollution is one of the grand challenges of the National Academy of Engineering (http://www.engineeringchallenges.org/). Thus, from an engineering perspective, it would be beneficial to develop sound engineering strategies for BNR design and operation that minimize both *aqueous* and *gaseous* nitrogen emissions. Based on this study, the measured emissions from some BNR processes were at least one order of magnitude higher than estimates derived from U.S. EPA emission factors (U.S. EPA, 2009). However, given that the emissions from other processes were clearly lower than current emission factor estimates (Table 4-1), the prospect of engineering-based minimization of N_2O emissions from WWTPs appears to be feasible.

Based on regression modeling results, BNR processes that avoid high NH_4^+-N, NO_2^--N and DO concentrations and transients thereof are expected to generate less N_2O, from both nitrification and denitrification. High NH_4^+-N, DO and NO_2^--N concentrations are typically encountered in under-designed and over-aerated nitrification reactors (Grady et al., 1999). Therefore, aerobic processes that avoid incomplete or intermittent nitrification and over-aeration are expected to have lower N_2O emissions. Additionally, processes that rely on more uniform spatial DO profiles to promote simultaneous nitrification and denitrification such as the oxidation ditch, are likely to have low N_2O emissions. Such processes avoid repeated switching between aerobic and anoxic conditions, which in conjunction with high NH_4^+-N and DO concentrations are a prime cause for nitrification driven N_2O emissions (Yu et al., 2010). An additional strategy to minimize N_2O emissions could be to minimize the peaking factor of influent nitrogen loading to activated sludge via flow equalization (Ahn et al., 2009). While flow equalization of primary effluent may be difficult because of the high flow rates, it might be possible in select WWTPs to blend high nitrogen containing centrate with primary effluent to equalize influent nitrogen loads.

These observations lead directly to future research that will be conducted during the next phase of this study.

7.7 Ongoing Studies and Future Perspectives

The next phase of this study will build upon the results obtained. Specifically, two directions have been selected for more detailed study. The first direction involves the implementation of process engineering measures to minimize N_2O emissions during BNR operation. Substantial insights have been gained during the course of the full-scale monitoring studies (Ahn et al., 2010), discussed in Chapter 4.0 and lab-scale studies (Yu et al., 2010; Lu and Chandran, 2010), discussed in Chapters 5.0 and 6.0 relating to factors that promote N_2O emissions in BNR processes. Using this information, the operation of a full-scale BNR process will be controlled to simultaneously minimize effluent total nitrogen concentrations and N_2O emissions fluxes. The study will be conducted in two parts, beginning with quantifying TN removal performance and N_2O emissions using the full-scale protocol developed for this study. Based on the data obtained, inferences will be made on factors contributing to N_2O emissions. Subsequently, process operation will be modified to achieve a balance between *liquid-phase* and *gaseous phase* nitrogen releases.

The second direction is to study emissions at a BNR or non-BNR facility that employs biofilm processes. Based on the full-scale monitoring results (Ahn et al., 2010), discussed in Chapter 4.0, the concerted action of both nitrification and denitrification can result in minimization of N_2O emissions during nitrogen cycling. Biofilm processes represent a prime example of nitrification and denitrification occurring in close spatial correspondence (rather than spatially distinct aerobic and anoxic zones, respectively). Therefore, the focus of this part of the study will be to examine the N-removal performance and N_2O generation potential of select biofilm-based systems and correlate once-again *liquid-phase* and *gaseous phase* nitrogen concentrations and contributors thereof.

APPENDIX A

FIELD PROTOCOL WITH QUALITY ASSURANCE PLAN

1.0 PROJECT DESCRIPTION AND OBJECTIVES

1.1 Problem Definition/Background

The push to achieve greater nitrogen removal from wastewater treatment plants, while minimizing infrastructure investments and operating costs, has resulted in the development of a wide range of innovative biological nitrogen removal (BNR) processes. However, BNR strategies could be a significant contributor to atmospheric N2O and NO depending upon the reactor configurations and operating conditions. In the future, as BNR is implemented at wastewater treatment plants around the nation, the flux of these gases to the atmosphere could significantly increase. Such increased releases would be a major concern since the greenhouse impact of nitrous oxide is about three hundred times that of carbon dioxide. Furthermore, nitric oxide is converted to nitrogen dioxide in the atmosphere, which is a precursor to photochemical smog (ozone).

1.2 Project Description

The goal of this WERF project is to characterize nitrogenous emissions from the activated sludge portion (only) of wastewater treatment plants. This project represents one of the first attempts at characterizing nitrogenous GHG emissions from wastewater treatment plants, and developing a methodology for collection of full scale plant data from a range of nutrient removal facilities in the United States. Building on previous work by the project team, this information will be integrated into an activated sludge model 1 (ASM 1) based mechanistic process model, which will be refined through this project through the addition of autotrophic pathways for N_2O and NO emission. The refined mechanistic model will allow the industry to codify the results of this research, and develop a tool that will aid in the prediction and therefore mitigation of N_2O, NO and NO_2 emissions from WWTPs utilizing a range of wastewater treatment processes. Ultimately, this could allow the wastewater sector to engineer strategies for wastewater treatment that minimize gaseous nitrogen oxide emissions.

1.3 Project Objectives

According to the guidance on Quality Assurance project planning provided by USEPA National Risk Management Research Laboratory (NRMRL), projects can be divided into four categories:

- Category 1 is a study intended to generate data for enforcement activities,
- Category 2 is a study to generate data in support of the development of environmental regulations.
- Category 3 is a applied research project to demonstrate the performance of accepted processes under defined conditions.
- Category 4 is a study to generate data to evaluate unproven theories or to develop potential processes.

This research project is a Category 3 study. The objectives of this project will be to:

1. Identify principal aqueous and gaseous intermediates in activated sludge tanks under different configurations, nitrogen loads, and operating conditions (i.e. extant dissolved oxygen concentrations)

2. Determine the relative mechanisms and contributions of oxidative and reductive pathways in gaseous nitrogen oxide production by activated sludge bacteria
3. Develop a tool based on ASM algorithms augmented to allow the results of this research to be codified and available for use. The tool will facilitate optimization of nutrient removal processes to minimize both aqueous and gaseous nitrogen GHG emissions.

These project objectives will be accomplished in part by direct data collection during three inter-related components: bench-scale reactors experiments conducted entirely by Columbia University under the direction of Dr. Kartik Chandran, Principal Investigator; characterization of nitrogen greenhouse gas emissions from full scale wastewater treatment operations (nitrification/ denitrification process tanks) also under the direction of Dr. Chandran; and collection of conventional wastewater parameters in conjunction with the full-scale gas emissions monitoring by participating wastewater treatment facilities under collaboration with Dr. Chandran. All of the participating wastewater treatment facilities have laboratory capabilities that are in compliance with their respective plant permits.

2.0 PROJECT ORGANIZATION

2.1 QA Management

WERF is a leader in research for the Clean Water sector (wastewater and stormwater utilities regulated under the Clean Water Act). WERF research also includes our volunteer advisory committees (Project Steering Committee), a group of highly-qualified subscriber practitioners, academics, and technology leaders, who provide oversight and technical direction to each research program to complement the WERF Program Director and the research teams. WERF actively abides by the applicable regulations established by U.S. EPA at 40 CFR Parts 30 and 31, as well as all applicable reporting, auditing, and financial management requirements. WERF will utilize its existing organizational management structure, systems, and processes already in place to support timely implementation of quality assurance (QA). WERF has instituted a quality management system in conformance with ANSI/E4 standards, and has adopted a highly-effective Quality Management Plan, which is reviewed and updated regularly.

2.2 Documentation and Records

A printed copy (MS Word®) of the most recently updated version of the QAPP will be present in the offices of the principal investigator, the Program Director and QA Project Officer. A printed master copy of the current QAPP will be maintained in a dedicated binder in the Environmental Biotechnology Laboratory, Columbia University (Mudd Building, Room 1041) for ready reference to laboratory personnel. In addition, the binder will contain hard copies of routinely generated calibration curves, audit reports, detailed standard operating procedures for each analytical method or instrument used in the project and copies of chain of custody forms.

A printed copy (MS Word®) of the most recently updated version of the QAPP will also be provided to the contact person identified at each participating and TCR facility. Detailed records of sampling and analytical procedures and the measured results will be maintained in the laboratory notebooks of the respective laboratory personnel. Laboratory notebooks at Columbia University will be maintained per Kanare, 1985 (*2*). Difficulties encountered during sampling and analysis will be documented in the laboratory notebooks. Documented sampling and analysis problems will be discussed and resolved during weekly meetings held at Columbia University under the supervision of Dr. Chandran and during monthly PSC conference calls.

Problems during sampling and analysis may also be resolved by contacting the Project QA Officer, if necessary. Additionally, the manufacturer of the monitoring and laboratory equipment being used may be contacted directly.

2.3 Responsibilities of Project Participants

The organization of responsibilities to ensure efficient functioning of various tasks associated with the project is per Figure P1. Dr. Kartik Chandran will serve as Principal Investigator and overall Project Manager. The research team will consist of Prof. Krishna Pagilla from the Illinois Institute of Technology, Dr. Dimitri Katehis from CH2M Hill, Dr. Sungpyo Kim, Research Scientist, Columbia University and Joon Ho Ahn, Doctoral Candidate Columbia University.

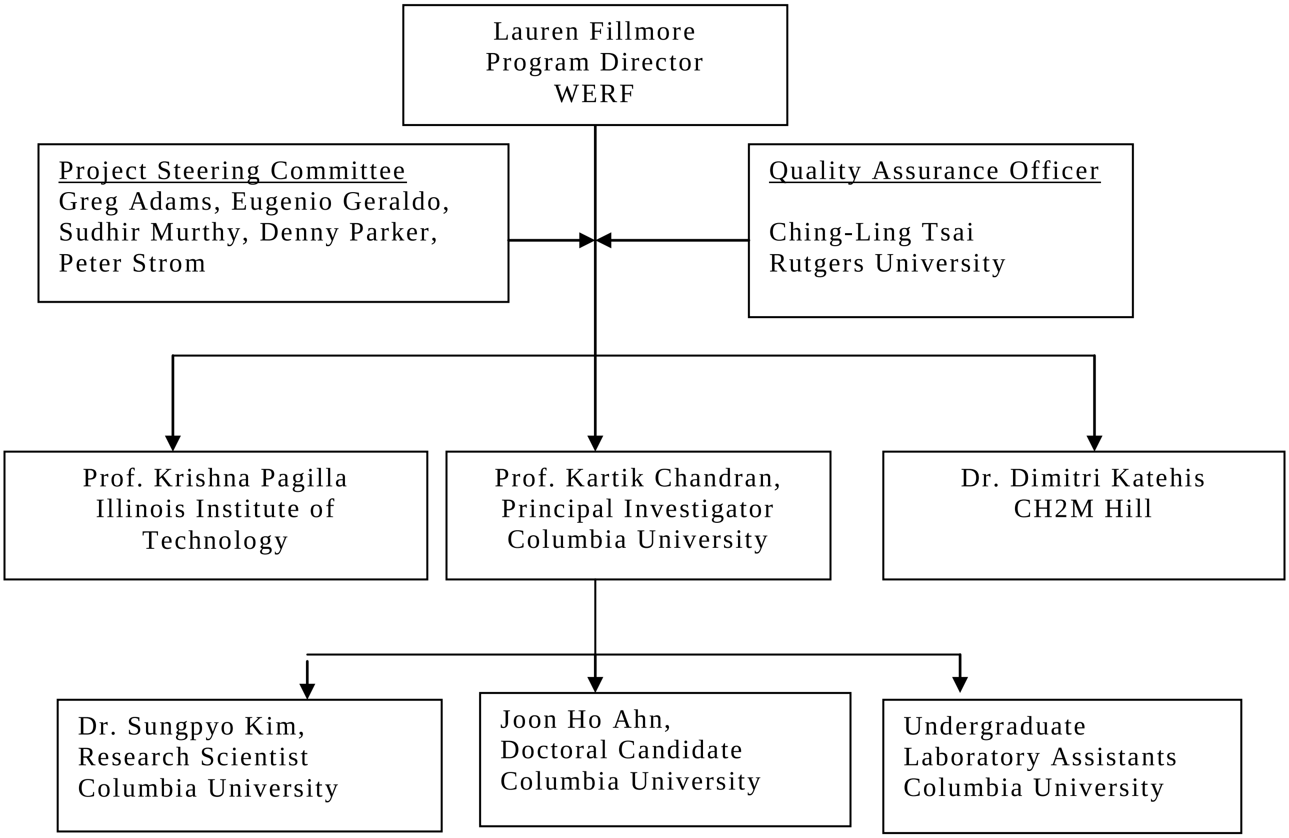


Figure A-1. Project Organization Chart.

2.4 Research Team Special Training Requirements/Certification

All laboratory personnel in the Columbia University Biomolecular Environmental Sciences (CUBES) Laboratories have undergone prior training on using different analytical instruments or methods. Additional training will be provided during new personnel initiation by respective equipment custodians.

All field and laboratory personnel from Columbia University will undergo a mandatory Chemical and Biological Safety Training Course before routine monitoring commences and at least once every year, thereafter.

Each analytical instrument in the Environmental Biotechnology Laboratory at the Columbia University has a designated Custodian. The equipment custodians are expected to be fully cognizant of the standard operating procedures of their respective equipment. In addition, the custodians are responsible for training new users in the proper operation of the instrument. Operator competence will be checked (after operator training) by evaluating single operator precision on five replicate analyses of an independently prepared check sample. The concentration of the check sample will be from 5 to 50 times the method detection limit for a given analysis (*3*)

3.0 EXPERIMENTAL APPROACH

3.1 Sampling Design for Bench-scale Reactors

To complement full-scale monitoring, lab-scale reactors will be run in different BNR configurations (full-nitrification, partial nitrification, denitrification with different carbon sources) and gaseous N emissions from these reactors will be quantified. In addition, reactor performance, biokinetics, microbial abundance and gene expression will be examined via chemical specific analysis, extant respirometry, light microscopy, and real-time RT-PCR, respectively. Such detailed analysis will allow us to determine the extent to which reactor operating conditions (DO, COD:N, L/W) impact release of gaseous nitrogen oxides via nitrification and denitrification. The Kartik Chandran Laboratories have optimized and applied nearly all molecular methods protocols required for this study for successful quantification of select bacteria in mixed microbial communities. Performance of the bench-scale nitrifying reactors operated at Columbia University will be monitored by sampling reactor mixed-liquor and effluent twice every week (Monday and Thursday) and measuring the concentration of analytes listed in Table A-1. Headspace gas analysis will be conducted once a week (Thursday). Initially, all samples will be analyzed within 24 h (preservation by storage at 4^{o}C (*3*)).

However, periods of more frequent sampling (e.g., during a toxic shock load) may necessitate storage of samples for a longer period of time and analysis of larger batches of samples. In such case, samples will be stored for a maximum of 28 d at 4^{o}C and pH < 2 (2 ml/L conc. sulfuric acid) or at $–20^{o}$C without acid addition (*3*) (See Table A-1) pending subsequent analysis. Representativeness of collected samples will be ensured by sampling at specified times and locations (i.e aerated zone, clarifiers, influent/effluent of reactors). Sample containers will be labeled with indelible ink identifying the date and time of sampling, sampling personnel, sample volume collected and analytes to be measured. Initially, all samples will be collected in 100% volumetric excess to permit quality control analysis or re-analysis for satisfying DQOs (See Table A-6). Sample containers will be washed and decontaminated as per standard protocols (*3*). Disposal of decontamination by-products that are classified as hazardous will be performed by the Department of Environmental Health and Safety, Columbia University or by wastewater treatment facility staff.

3.1.1 Sample Handling and Custody Requirements

Sampling handling and custody will be recorded in detail as per Figure P3 for analyses conducted in Environmental Biotechnology Laboratories at Columbia University. The chain of custody form will be filled out for each sampling and analysis exercise by the respective personnel performing sampling and analysis. Completed chain of custody forms will be stored in a dedicated Log Binder (See Section 9.3).

3.1.2 Measurements Performed during Bench-scale Testing

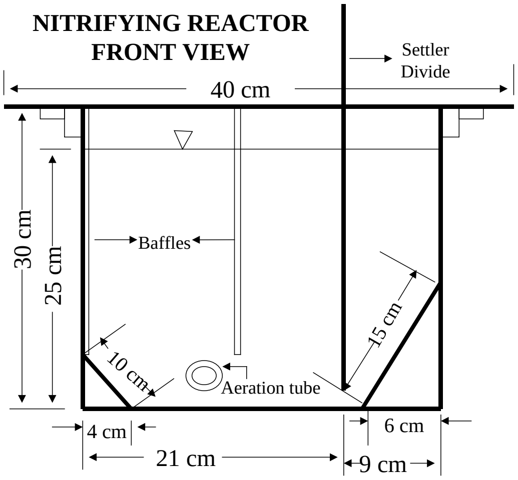
Measurements of typical wastewater parameters and state variables will be performed per methods approved by the U.S. EPA as provided in Table A-1.

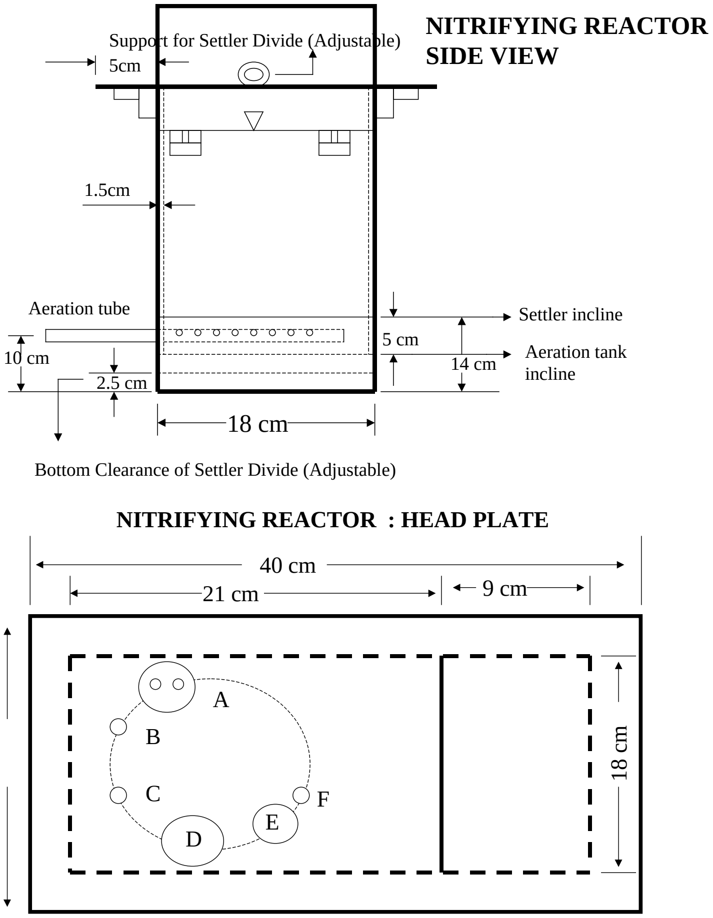
Table A-1. Methods for Measurement and Analysis.

Name of Chemical or Method	Method	Method Detection Limit (per US EPA 40 CFR 136, App. B)	Standard Method (*3*)
pH		Not applicable	4500 H^+
Chemical Oxygen Demand : Colorimetric	EPA 0410.4$^{=}$	12 mg COD /L	5220C
NH_3-N Potentiometric : (ISE),	EPA 0350.3$^{=}$	0.15 mg-N/L	4500-NH_3 B 4500-NH_3 D
NO_2^--N : Spectrophotometric,	EPA 0354.1$^{=}$	0.002 mg-N/L	4500-NO_2^- B
NO_3^--N : Potentiometric : (ISE),	Standard Method	0.2 mg-N /L	4500-NO_3^- D
Dissolved Oxygen (DO) : Membrane Electrode (Probe)	EPA 0360.1$^{=}$	Not applicable	4500-O G
NOx	Chemiluminescence	NA	
N_2O	Infra-red	NA	
Automated data acquisition of DO measurements	Analog output	0.009* mg /L	

Note : All above analyses performed at the Environmental Biotechnology Laboratory, Columbia University
$^{=}$: (*4*).
* : based on least count of the instrument used for measurement

Sample source: Bench-scale Nitrification-Denitrification Reactors
Location: Columbia University, New York, NY





A: Acid and Base; **B** : Feed; **C** : Sampling; **D** : DO Probe; **E** : pH Probe

F : Temperature Probe (Port sizes in proportion)

Figure A-2. Design Specifications of Benchscale Nitrifying Reactor.

ENVIRONMENTAL BIOTECHNOLOGY LABORATORY
COLUMBIA UNIVERSITY
CHAIN OF CUSTODY FORM

Project: Greenhouse Nitrogen Emission from Wastewater Treatment Operations
(U4R07)

Sample No.	Sample Location	Sample Type	Collected By	Sample Date	Sample Time	Preservation	Date Analyzed	Sample Relinquished		Sample Received	
								Name	Date	Name	Date

Figure A-3. Sample Handling and Custody Form.

3.2 Sampling Design for Full-Scale Monitoring

The treatment trains of selected wastewater treatment plants that are accomplishing nitrification and denitrification will be characterized based on their liquid phase and gas-phase nitrogen concentrations and speciation. Testing will be conducted at each location during a sampling campaign during which gas phase monitoring will be conducted in real-time continuous mode and liquid phase sampling will be conducted via discrete grab sampling. Trends and variations in gaseous emissions and speciation will be ascertained. This sampling effort will assist in the development of process operating criteria that minimize both gaseous and liquid phase nitrogen emissions from wastewater treatment facilities. Sampling for nitrogen GHG compounds and precursors in both the air and liquid phases will be performed by Columbia University researchers. Conventional wastewater parameters will be sampled and analyzed by facility personnel corresponding to a preset regime in collaboration with the principal investigator.

Monitoring of the liquid-phase and the gas-phase will be conducted once in warm temperature conditions (i.e. summer, early fall), and cold temperature conditions (winter/early spring) in the Northeast and Midwest and twice in plants along the West Coast (Fall and Spring), not subject to significant temperature changes.

4.0 SAMPLING PROCEDURES – NITROGEN GHG EMISSIONS

Sample source: Treatment train from full scale wastewater treatment facilities
Location: Several BNR and non BNR plants around the country as outlined in the list in the list of participating facilities (Page 2)

4.1 Sampling Design

The overall procedure for measuring N_2O, NO and NO_2 fluxes from the head-space of activated sludge tanks involves a variant of the EPA/600/8-86/008 and the South Coast Air Quality Management District (SCAQMD) tracer methods. This variant has been developed to measure those sources that have a relatively high surface flux rate when compared to diffusion which facilitates increased sampling at of composting and wastewater treatment plants across the country. A detailed description of the procedure in provided in Appendix A - Protocol.

Commercially available replicas of the US EPA surface emission isolation flux chamber (SEIFC) will be used to measure gaseous N fluxes from activated sludge reactors. The SEIFC consists of a floating enclosed space from which exhaust gas is collected in a real-time or discrete fashion. Since the surface area under the SEIFC can be measured, the specific flux of the gaseous compound of interest can be indirectly determined. The SEIFC 'floats' on the activated sludge tank surface and several replicate measurements can be taken at different locations in a single tank as well as from different tanks (nitrification, denitrification) along a treatment train.

The SEIFC is also equipped with mixing (physical mixer or via sweep gas circulation) to ensure adequate gas and in some cases, an online temperature probe. The SEIFC is currently one of the few devices accepted by the USEPA for measuring gaseous fluxes (*1*) and as such will be employed for this study. Gas-phase analyses will be conducted via infra-red (N_2O) and chemiluminescence (NOx) methods. Detailed description of the analyzer equipment is provided in Appendix A- protocol.

In general, sampling will be conducted at multiple locations of the activated sludge train in each wastewater treatment facility. These locations the aerobic, anoxic and anaerobic zones, depending upon the configuration of the given facility.

Full-scale measurement of gas fluxes will be conducted at different locations along the activated sludge train at each full-scale wastewater treatment facility. Based on a fundamental understanding of the biological pathways that contribute to N_2O fluxes from activated sludge, the transition between the aerobic and anoxic zones is expected to be point contributing most to these fluxes.

Nevertheless, at each plant, N_2O, NO and NO_2 emissions will be monitored from anoxic and aerobic zones. Typically, we anticipate sampling at one point in each anoxic zone and each aerobic zone with active nitrification along the treatment train.

During the course of the gas phase sampling, liquid phase samples will be collected adjacent to the hood location. The samples will be filtered immediately upon collection in the field and analyzed by host plant personnel for ammonia, nitrite and nitrate concentration, utilizing readily available field methods (i.e. a Hach Kit). As the primary purpose of these measurements is to ensure the presence of the targeted nitrogen species, without consideration to accuracy in the concentration measurements, the simplest available field method will be used for these preliminary measurements. Profiles of the nitrogen species along the aeration tank will be collected using the plants standard sampling and analysis procedures as outlined in Section 6.

4.2 Sampling Methods for Nitrogen GHG Emissions

4.2.1 Gas Phase Sampling Method in Aerobic Zones

- Seal all but one vent in the flux chamber and connect high sensitivity pressure gauge to the one open vent.
- Lower flux chamber into aerobic zone (bottom of rim should be below the surface of the water by 1-2 inches minimum).
- Wait for N_2O analyzer to equilibrate based on stability indicator (<0.03)
- Pull the flux chamber up. Open two vents and connect the N_2O analyzer, NOx analyzer. The other vents should be left open to atmosphere.
- Record temperature of the gas in the flux chamber using a digital temperature gauge (Fisher Scientific number 15-077-8 or suitable alternate)
- Care must be taken not to have the flow going to the two analyzers exceed the gas-flow rate from the flux-chamber. Otherwise, atmospheric air will be drawn in through the vents in the flux chamber.

4.2.2 Determination of Gas Flow Rate from the Flux Chamber in Aerobic Zones

- Disconnect N_2O and NOx analyzers and connect one outlet vent to the inlet line of a field gas chromatograph equipped with a thermal conductivity detector. Close the other vent.
- Introduce tracer gas (10% He, 90% zero air) through an inlet vent into the flux chamber at a known flow rate (for instance 1L/min).
- Measure the concentration of He gas exiting the flux chamber (protocol in appendix A).
- Based on the measured He concentrations, calculate via linear algebra the flow rate of aeration tank headspace gas entering the flux chamber (equation 1 provided in Appendix).

4.2.3 Gas Phase Sampling Method in Anoxic Zones

- Seal all but one vent in the flux chamber and connect high sensitivity pressure gauge to the one open vent.
- Lower flux chamber into anoxic zone with a (1-2 inch minimum submergence, into the liquid surface)
- Wait for N2O analyzer to equilibrate based on stability indicator (<0.03)
- Pull the flux chamber up. Open two vents and connect the N_2O analyzer, NOx analyzer and the **sweep gas pump** (**Note: sweep gas only used during anoxic zone sampling)**. The other vents should be left open to atmosphere.
- Record temperature of the gas in the flux chamber using a digital temperature gauge (Fisher Scientific number 15-077-8 or suitable alternate).
- Care must be taken never to have the flow going to the two analyzers exceed the sweep gas rate or dilution air will be drawn in through an opening in the chamber.

4.2.4 Determination of gas flow rate from the flux chamber in Anoxic Zones

- Disconnect N_2O and NOx analyzers and connect one outlet vent to the inlet line of a field gas chromatograph equipped with a thermal conductivity detector. Close the other vent.
- Introduce sweep gas to the chamber at a flow rate of 4L/min and wait 6 min for steady-state.
- Introduce tracer gas (10% He, 90% zero air) through an inlet vent into the flux chamber at a known flow rate (for instance 1L/min).
- Measure the concentration of He gas exiting the flux chamber (protocol in appendix A).
- Based on the measured He concentrations, calculate via linear algebra the flow rate of aeration tank headspace gas entering the flux chamber (equation 2 provided in Appendix).

Table A-2 summarizes the data recording requirement checklist that needs to be followed for flux-chamber set up and operation. Additional analytes can be added by sampling teams based on a case specific basis.

Table A-2. Checklist for Flux Chamber Set-up and Operation in Field.

Measurement	**Sampling Location 1**	**Sampling Location 2**	**Sampling Location 3**
Gas flow rate from flux chamber			
Gas temperature in flux chamber			
Wastewater temperature			

4.3 Continuous and Real-Time N_2O Measurement

1. Turn on the power by pressing the on/off switch on the front panel. The display should turn on and green (sample) status LED should be energized. The green LED should blink indicating the instrument has entered the HOLD-OFF mode. Sample mode can be entered immediately by pressing the EXIT button on the front panel. The red "fault" light will also be on until the flows, temperatures and voltages are within operating limits. Clear the fault messages. After the warm-up, review the TEST function values in the front panel display by pushing the left most keyboard button labeled TEST.
2. Activate the instrument DAS data acquisition and set the sampling frequency for 1 sample per minute
3. Start data acquisition.
4. Connect the inlet tubing of the analyzer to the outlet tubing from the SEIFC securely using a standard 1/4” compression fitting connector.
5. Acquire data for about 20 min in anoxic zones and about 10 min in aerobic zones **after** stable readings are obtained- as indicated by the stability indicator on the N_2O analyzer.
6. Terminate the DAS software and immediately save the acquired data.
7. Repeat steps 2-5 for each sampling point and sampling locations (individual tanks).

Measurement Range

0-1000 ppm

Calibration
At the beginning and end of each sampling event, the instrument will be calibrated using "zero gas" and N_2O standard gas as per manufacturer's instructions.

4.4 Continuous and Real-time NO and NO_2 Measurement

1. Turn on the power by pressing the Power switch on the front panel and the external vacuum pump and wait till the display reads "**MEAS**" (this should typically take less than thirty minutes).
2. Activate the instrument data acquisition software and set the sampling and data save frequency for 1 sample per minute and 10 minutes, respectively. Start data acquisition.
3. Connect the inlet tubing of the analyzer to the outlet tubing from the SEIFC securely using a standard 1/4" compression fitting connector.
4. Acquire data for about 20 min in anoxic zones and about 10 min in aerobic zones **after** stable readings are obtained- as indicated by the stability indicator on the N_2O analyzer.
5. Terminate the CLD software and immediately save the acquired data.
6. Repeat steps 2-5 for each sampling point and sampling locations (individual tanks).

Measurement Range
Adjustable, 0-100 ppm

Calibration
At the beginning and at the end of each sampling day, the instrument will be calibrated using "zero gas" and NO standard gas as per manufacturer's instructions.

4.5 Measurement of Liquid-Phase N_2O Concentrations

In addition to measuring gaseous phase N_2O concentrations in the headspace of aerobic and anoxic zones, the liquid-phase N_2O concentrations will be measured to discriminate between N_2O generation in the liquid phase and N_2O emission in the gas phase. Liquid-phase N_2O concentrations will be measured using a polarographic Clark type electrode (Unisense, Aarhus, Denmark). For additional details of the liquid phase measurements summarized in this section, please refer to the Appendix.

1. Withdraw about 20 ml sample from test reactors in 50 ml conical centrifuge tubes or alternate similar containers (plastic or glass beakers are acceptable).
2. Take out the microsensor from the calibration chamber (containing deionized water), rinse out with deionized water, and mop dry with a tissue.
3. Immerse the microsensor into the samples. **Proceed as rapidly as possible after acquiring the sample**.
4. Record the numbers from the display on the picoammeter. The measurement numbers should be stable within one minute.
5. Pull out the microsensor, rinse out and place it back into the calibration chamber.
6. Repeat steps (1) ~ (5) for each sampling point and location.

4.6 Sample Collection Responsibilities

The measurement of nitrogen GHG emissions and collection of samples using the flux chamber will be done by Columbia University researchers and field technicians under the direct supervision of Dr. Kartik Chandran. As the measurement of these parameters will be conducted by real-time analyzers or *in-situ* liquid probes, there is no need for sample handling and preservation. The real-time data from the analyzers or probes will be automatically downloaded on to a field computer or recorded in laboratory notebooks under the control of the Columbia University researchers. All electronic data will be backed up immediately upon return to New York to a duplicate location in the Environmental Biotechnology Laboratories at Columbia University. Additionally, where feasible electronic data will be stored on a temporary disk drive (in addition to the PC hard drive) during the field testing events.

5.0 SAMPLING PROCEDURES – WASTEWATER CHARACTERIZATION DATA

Sample source: Treatment train from full scale wastewater treatment facilities
Location: Several BNR and non BNR plants around the country

5.1 Sampling Design

Facilities that are selected to participate in an initial sampling effort will need to characterize influent flow, organics and nitrogen concentrations to the facility, in preparation for the detailed liquid and air measurement campaign. For the initial sampling the following parameters will be monitored from the secondary process:

- Influent Flowrates (minimum of once per hour)
- Influent and Effluent Ammonia (up to 8 times per day)
- Influent and Effluent Nitrite and Nitrate
- Influent and Effluent COD (assume once per hour, can be reduced depending on variability at site)

Additionally, diurnal performance and in-tank profiles will be gathered at the time of the N GHG phase sampling. To the degree feasible, all liquid phase analyses will be according to approved methods and protocols that are used to gather data for regulatory NPDES or SPDES permits at the participating facilities.

Note: To the extent possible, the sampling team will work with the laboratory personnel of the participating facilities to include data from online analyzers present at a given test site to avoid duplication of data gathering efforts.

5.2 Sampling Methods

Sampling will be conducted in accordance with the host WWTP’s standard operating procedures, after review of said procedures by the project team. Sampling will involve use of autosamplers and manual sampling devices, as appropriate to support the sampling.

5.3 Sample Collection Responsibilities

The collection of conventional wastewater samples for analysis of parameters in Table A-3 will be a conducted by facility personnel who usually collect operational and compliance samples for each participating facility. In advance of each sampling event, the Columbia University researchers will consult with laboratory personnel to ensure that samples for the conventional parameters are collected during the GHG monitoring event to meet the requirements of both the research design and the host facility’s laboratory operating procedures. .

5.4 Sample Handling and Custody Requirements

To the extent possible, the host utility’s sample handling and custody requirements will be utilized for each field sampling campaign. To confirm adequacy of procedures, approximately two weeks prior to the full scale testing the host utility's procedures for field sample handling and chain of custody will be reviewed with the project team. At that time, if modifications are deemed necessary by the project team, they will be defined and documented in the Site Specific Sampling Protocol.

6.0 TESTING AND MEASUREMENT PROTOCOLS

6.1 Analytical Methods Requirements for Wastewater Characterization Data

Table A-3 provides the sample location, the chemical parameter, sample container, preservative and holding time for samples to be collected during the operation of the bench scale reactors at the Columbia University Laboratory. For the full scale field testing, each host utility’s laboratory will follow their specific laboratory standard operating procedures for each parameter. Standard Operating Procedures from participating laboratories will be included in the site specific protocol.

Table A-3. Sampling Specifications: Columbia University.

Name of Chemical or Method	Measurement Classification			Sample Location	Sample Volume[*] (ml)	Sample Preservation	Maximum Holding Time
	Type	Frequency	Sample Equipment				
Bench Scale Nitrifying Reactors							
pH (Bench scale reactor)	C	NA	Bench scale reactor	Reactor	NA	NA	None, online
Chemical Oxygen Demand – Colorimetric	I, C	2/7 d	35 ml glass vial	Reactor, Effluent	8	4°C	1 d
NH_3-N Potentiometric (ISE)	I, C	2/7 d	200 ml glass bottle	Effluent	80	4°C$^{\Psi}$	1 d
NO_2^--N Spectrophotometric	I, C	2/7 d	200 ml glass bottle	Effluent	40	4°C$^{\Psi}$	2 d
NO_3^--N Potentiometric (ISE)	I, C	2/7 d	200 ml glass bottle	Effluent	40	H_2SO_4, pH < 2	28 d
Dissolved oxygen (Extant Respirometry)	C	4 Hz	100 ml respirometric vessel	Reactor	200	NA	NA
N_2O	C	1/7 d	Gas sampling assembly[**]	Reactor headspace	NA	NA	NA
NOx	C	1/7 d	Gas sampling assembly[**]	Reactor headspace	NA	NA	NA
Dissolved oxygen (Bench scale Reactor)	C	NA	Bench scale reactor	Reactor	NA	NA	None, online

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[*]: The tabulated sample volume is twice that required for routine duplicate analysis and is apportioned into two sample containers. The additional volume is collected to determine quality control measures such as accuracy (analysis of spiked samples), precision (duplicate analysis) and to account for potential sample loss while handling or analysis. (Also see section 1.6)

C : continuous measurement I : intermittent measurement

Frequency of measurement applies only to continuous measurements

[Ψ] : Storage at 4°C. However, the biomass is removed from the sample via centrifugation at 3500 g for 10 minutes. Biomass removal arrests further biochemical oxidation of NH_4^+-N and NO_2^--N. NA : Not applicable **: See protocol

6.2 Standardization of overall N-GHG Measurement Methodology

The overall procedure for measuring N_2O, NO and NO_2 fluxes from the head-space of activated sludge tanks involves a variant of the EPA/600/8-86/008 and the SCAQMD tracer methods. Gas-phase analyses will be conducted via infra-red (N2O) and chemiluminescence (NOx) analyzers.

In the absence of an approved (USEPA or ASTM) method for N2O in air or water, method modification was necessary to meet project objectives and measure N2O emissions. To evaluate the performance of the measurement of N_2O, NO and NO_2 fluxes using the procedure developed by the researchers, three side-by-side monitoring events were conducted along with the research procedure during the first sampling event at a step feed BNR facility. In addition to the research protocol performed by Columbia University staff, two additional side-by-side monitoring events were conducted as follows:

- Plant wastewater research engineers measured fluxes using the EPA isolation flux chamber and SCAQMD tracer method (confirm)but with a photo acoustic analyzer to directly determine N2O.
- Chuck Schmidt, Ph.D. used the textbook EPA isolation flux chamber and SCAQMD tracer dilution method to measure the flux and the following analytical methods to measure ozone precursors and GHGs.

Table A-4. Summary of Analytical Methodology by C. Schmidt.

Method/Species	**Technique**	**Application**
ASTM Method 1946- Permanent Gas Analysis	GC/TCD	Relevant Fixed Gases: CH4, CO, CO2, and Helium as a separate analysis
NIOSH 6600	FTIR	N2O, NO, NO2

These side-by-side tests using the NIOSH 6600 method were not designed to validate the modified analytical approach to establish an approved methodology; however, they provided an independent verification that the approach followed as part of this WERF project accurately measured N GHG emissions to meet the objectives of this research, for zones where concurrent side-by-side measurement was conducted.

Based on this side-by-side comparison, it was further recommended that the WERF project should consider the He tracer method (based on ASTM D1946) to measure gas flow rate from the flux chamber. This recommendation has since been incorporated in this protocol

7.0 QUALITY CONTROL REQUIREMENTS AND CORRECTIVE MEASURES

7.1 Quality Control (QC) of Laboratory Samples

Unless explicitly stated, these are applicable solely for the bench-scale portion of the study. Since established QC procedures are already in place at field test facilities, they will supersede the QC procedures outlined in this QAPP.

Approximately 20% of the samples will be designated as QC samples: Recovery of known additions: 5%; split samples: 5% (bench-scale testing only); samples for duplicate analysis: 10%. The acceptance criteria for different QC measures are listed in Table A-5. Note that known spikes are not feasible in the field for gas phase measurements due to transport limitation of hazardous gas cylinders.

Table A-5. Quality Control Indicators of Analytical Data.

Quality Control Indicator	**Sample Type**	**Frequency**	**Parameter**	**Acceptance criterion (%)**
Precision	Check standard	1 per 10	RPD	± 25
	Field Duplicate	1 per 10	RPD	± 25
	Lab Duplicate	1 per 10	RPD	± 25
Accuracy	Known spike	1 per 20	% recovery	75 – 125
Completeness	All	Annual	% missing	To be determined
Performance audit	Known sample	≥4/Year	RPD	± 10

RPD : Relative Percent Deviation (see Equation 4 below)

Data Quality Objectives (DQOs) will be expressed in terms of the following data quality indicators. The developed DQOs will be used to accept or reject data obtained during this study.

7.1.1 Precision

Precision is a measure of the closeness with which multiple analyses of a given sample agree with each other. Precision will be expressed as relative percent difference (RPD) of duplicate measurements (X_1 and X_2).

$$RPD = \frac{(X_1 - X_2)*100}{((X_1 + X_2)/2)} \qquad (4)$$

Instrument or method precision will be determined by duplicate analysis of stable standards. Overall precision of the study will be determined from duplicate samples subjected to identical sampling, sample preparation and analyses. Overall precision measures will reflect random errors in sampling, and variations in sample preparation and analysis. The precision of both field and lab duplicates will be measured (*5*).

7.1.2 Accuracy

Accuracy reflects the degree of confidence in a measurement. The accuracy of measurement techniques and analytical instruments will be checked by examining the percent recovery of sample spikes of a known composition. The percent recovery is defined as :

$$\text{\% recovery } = \left(\frac{C_S - C}{s} \right) x100 \qquad (5)$$

where :

C_S : spiked sample concentration
C : sample background concentration
s = concentration equivalent of analyte added to sample

Note : The total concentration after the sample spike should be within the linear calibration range of the method. Further, the volume change due to the spike should be negligible (*3*)

7.1.3 Representativeness

Representativeness is the extent to which measurements actually depict the true environmental condition or population being evaluated. For lab-scale reactors operated with constant influent loading, grab samples will be collected to ensure spatial (aerobic or anoxic zone, settling chamber) and temporal (consistent time and day of sampling during the week for a continuous flow reactor or consistent point along a sequencing batch reactor cycle) representativeness. This metric applies only to the lab-scale reactor element of the study.

7.1.4 Completeness

Completeness is a measure of the number of samples needed to provide useful information describing the system under investigation, compared to the total number of samples collected. Initially, for bench-scale reactors, all samples will be collected in 100% excess to permit quality control analysis or re-analysis owing to sample loss or data not complying with set DQOs. For instance, four samples will be collected, although only duplicate analysis will be performed routinely. Quality control analysis will be performed on 20% of the total samples routinely analyzed. Completeness will be expressed as the percentage of the total number of measurements that are judged valid according to data quality objectives standards.

7.1.5 Comparability

Comparability is the extent to which data from one study can be compared directly to past data. The influent dynamics of aqueous and gaseous nitrogen species from the lab-scale reactors will be compared to those from similar operating conditions based on past records maintained in the lab.

7.1.6 Recovery of Known Additions

The accuracy of an analysis will be assessed by measuring the recovery of a sample spiked with a known concentration of a given analyte. 10% of the total samples collected will be used for the recovery of known additions. The analyte spike concentration will be between 5 and

50 time the MDL or between 1 and 10 times of the ambient concentration, whichever is higher (*3*). Again, this analysis is restricted to liquid-phase samples.

7.1.7 Analysis of Externally Supplied Standards

Externally supplied standards will be analyzed whenever analysis of known additions does not result in acceptable 25% recovery or once every day, whichever is more frequent (*3*). The concentrations of the standards will be between 5 and 50 times the MDL or near ambient sample levels (*3*). External standards will either be certified laboratory control standards or laboratory standards prepared independently from calibration standards (*3*).

7.1.8 Calibration with Standards

The electrical response of all analytical instruments will be linearly correlated to at least three analyte concentrations before each analysis. Typically, laboratory measurements that are within the linear calibration range will be reported. If the entire calibration range is not covered during a certain measurement, concentrations above the highest standard will be reported only if the following conditions are satisfied (*3*):

Past evidence from earlier calibration curves obtained at identical instrument settings
Measured value is less than 1.5 times the highest calibration standard.

On the lower end, the lowest reported value will be the MDL, provided that the lowest calibration standard is less than 10 times the MDL. If a method requires the response of blanks to be subtracted from the response of test samples, negative results will be reported as such or as below the limit of detection (*3*).

7.1.9 Analysis of Duplicates

10% of the total samples or one per analytical batch (whichever is more frequent) will be analyzed in duplicate. Using duplicate measurements, the precision of analytical technique (lab duplicate) or precision for the entire project (field duplicate) will be evaluated.

7.2 Performance Audits

7.2.1 Monitoring Lab Analysis (Bench-scale Testing)

Performance audits to monitor lab performance will entail analysis of unknown samples obtained from a lab supply company (e.g., Fisher Scientific Co., NJ). Performance audit samples will be analyzed at Columbia University before analysis of actual samples. Prior analysis of performance audit samples will ensure that the laboratory is well equipped in terms of (a) instruments, (b) standard operating procedures and (c) competent personnel for the continuous monitoring operation. A list of the audit activities and results will be present in the office of the principal investigator. If analysis of performance audit samples is not satisfactory (measured average outside ±10% of the actual audit sample value), errant data between two consecutive audits may be discarded and re-sampling or re-analysis may be warranted.

7.2.2 Monitoring Standard Operating Procedures

One unscheduled performance audit will be performed by the QA project officer. The audits will be conducted using a checklist made to document the protocol followed by the sampling crew and analysts while sampling, sample handling and storage, analysis, reporting of results (Table A-6). Any deviations from the standard operating procedures maintained will be recorded in the laboratory notebooks of sampling personnel and corrective action will be taken to minimize future discrepancies. Further, in such case, the results obtained via non-standard protocols will be reviewed. If necessary, the results will be discarded and the stored samples will be re-analyzed as appropriate and if available. If the modification in the standard operating procedure improves the existing method, changes will be incorporated in the standard

Table A-6. Sample Performance Audit for Sampling Nitrifying Bench-Scale Reactors.

Standard Procedure	Performed	Remarks
Sample point from well mixed region (below aeration tube)	Yes	Tube cleaned thoroughly before introducing into reactor
Sample labeled and particulars entered in logbook	Yes	Date and time of sample Sampling personnel Sample volume Analyte to measure : NH_4^+-N, NO_3^--N, tCOD
Sample split evenly	No	Sample not well mixed during split
Sample acidified	Yes	Conc. H_2SO_4, (2ml/L)
Sample storage	Yes	4^oC, 28d holding time

7.3 Corrective Measures

Unsatisfactory data (not meeting DQO specifications) could result from flaws in the instrument or poor analyst skills. In case of unsatisfactory data quality, corrective measures will include a thorough trouble-shooting of analytical instruments as recommended by the manufacturer and re-calibration of instruments using fresh reagents and standards. Further, the Standard Operating Procedure performance audits will also be checked to ensure competence of analysts and to conduct re-training, if necessary. In any case, deviant data will be discarded and re-sampling or re-analysis of stored samples will be performed.

7.4 Instrument Calibration, Maintenance and Quality Control Checks

Equipment used in continuous reactor operation such as pumps (Cole-Parmer, IL), DO controllers (Cole-Parmer, IL) or pH controllers (Cole-Parmer, IL) will be checked daily as part of routine reactor maintenance. In case of malfunction, the instrument will be disconnected from the reactor and re-calibrated, or replaced. The reactors will be temporarily shut down only if necessary. Currently, we have an extra set of reactor accessories in our laboratory for emergency repair measures.

The filling solution of the HNU ammonia gas sensing electrode will be changed once every three weeks, and the electrode membrane cap will be changed once every three months (HNU systems, MA). When not in use for short periods, the electrode will be stored in a 140 mg/l NH_4^+-N solution. The manufacturer of the NO_3^--N ISE (Hach Co., CO) recommends that the electrode membrane tip should be changed whenever a low slope of the calibration is observed (< 55 mV/decade). During continuous use, the electrode will be stored in a 100 mg NO_3^--N/L solution without ionic strength adjustor (ISA) added.

For NH_4^+-N and NO_3^--N measurement using potentiometric methods and NH_4^+-N measurement using the phenate method, a fresh calibration curve (at least three points, e.g., 10, 100, 1000 mg/l, encompassing the concentrations to be measured) will be constructed for every analytical batch. From past experience and current analysis, the variability in calibration curves for colorimetric COD and NO_2^--N measurement is small and therefore these calibration curves will be updated once every month. The individual points of the calibration curve will be generated from duplicate measurements. Calibration standards will be purchased from commercial vendors (e.g., from HACH Co. for COD standards) or prepared according to Standard Methods (e.g., for NH_4^+-N, NO_2^--N and NO_3^--N) (*3*). All calibration curves will be stored on a personal computer to compare time-dependent variation in instrument characteristics or degradation of standards. After analysis of ten samples, a single-point calibration will be performed (preferably at the midpoint of the multi-point calibration. If the single-point continuing calibration deviates by more than 25% from that of the multi-point curve, the analytical run will be terminated. A new multi-point calibration will be performed and all samples analyzed after the last satisfactory single-point calibration curve will be re-analyzed. Weighing devices such as balances or scales will be checked with class S weights once every month.

For continuous reactor operation, the feed pumps will be calibrated manually once every week. The pH and DO meters used for continuous monitoring and control will be respectively calibrated by using standard pH solution or saturated DI water at reactor operating temperature (25°C) once every month. All pipettes will be calibrated according to manufacturers' instructions once every six months.

The N_2O and NOx analyzers will be calibrated at least once every six months (as per manufacturers' instructions and past measure of their stability) and before anf after each sampling campaign using zero gas and N_2O (500 ppm) and NO (10 ppm) gas standards.

7.5 Inspection/Acceptance Requirements for Supplies and Consumables

All reagents used in reactor operation and chemical or biological assays will be of highest purity necessary (typically ACS grade). Appropriate tubing and hoses will be used for specific applications (e.g., nontoxic Pharmed® tubing will be used to supply feed solution to reactors, Masterflex® corrosion-resistant tubing will be used for intermittent acid or base addition to reactors for pH control). Reactor tubing will be routinely checked visually for microbial growth and cleaned using DI water, once every two weeks or more frequently, if necessary. Fresh tubing will installed every two months. Newly purchased supplies (e.g., Sample containers) will be washed using standard methods (*3*) before use. Evaluation of possible measurement artifacts due to sampling or storage equipment will be part of QC analysis (Section 7.1).

8.0 DATA REPORTING, DATA REDUCTION, AND DATA VALIDATION

Periodic data generated during the course of this study will be compiled weekly by the individual personnel conducting the respective experiments and analyses. The compiled data will be presented during weekly progress meetings held under the supervision of Dr. Chandran at Columbia University and monthly PSC conference calls.

8.1 Data Verification

The process of data verification determines whether data has been collected in accordance with specifications outlined in the QAPP. The four criteria for data verification are compliance, correctness, consistency and completeness.

Compliance: Compliance of data acquired during this project will be evaluated in terms of adherence to SOPs and satisfying QC criteria outlined in this QAPP. Examples of data compliance evaluation tasks include:

Data Compliance Evaluation Task	Performed by
Staff Training and Certification	Project Manager
Sample Custodian Assignment	Project Manager
Field Data Collection Audit	Project QA Officer
Calibration of Instruments	Sampling Personnel
Confirming Verification of Calibration	Sampling Team Leader
Calibration Corrective Action Audit	Sampling Team Leader and Project QA Officer
Sample Preservation and Handling	Sampling Personnel

Correctness: Correctness of acquired data will be determined by checking if data analysis calculations were performed in accordance with properly documented and properly applied algorithms. Examples of data correctness evaluation tasks include:

Data Correctness Evaluation Task	Performed by
Instrument Inspection and Maintenance Audit	Sampling Team Leader
Instrument Calibration Review	Sampling Team Leader
Data Recording Audit	Project QA Officer
Data Reduction Audit	Project QA Officer
Data Transformation Audit	Project QA Officer
Raw Data Audit	Sampling Team Leader

Consistency: Consistency refers to the extent to which data collection and data reporting procedures were done in a reproducible manner. Consistency ensures that reported values of any given parameter or state variable are identical, when used at different times or locations in the Project. Examples of data consistency evaluation tasks include:

Data Consistency Evaluation Task	Performed by
Data Handling Audit	Project QA Officer
Data Transmittal Review	Project QA Officer

Completeness: Completeness is the extent to which all data necessary to perform validation analysis were actually collected. Completeness is based on DQOs outlined in the QAPP. Examples of data completeness evaluation tasks include:

Data Completeness Evaluation Task	Performed by
Documentation of Sampling Corrective Action	Sampling Team Leader, Sampling Personnel
Sample Records Documentation and Audit	Sampling Personnel
Sample Transport Documentation and Audit	Sampling Team Leader

Data Management audit	Project QA Officer
Chain of Custody Documentation	Sample Custodian
Sample Identification Audit	Project QA Officer
Instrument Inspection and Maintenance Documentation	Sampling Personnel
Traceability of Standards Review	Sampling Team Leader
Documentation of Calibration Corrective Action	Sampling Personnel

The results of data verification will be presented to the Project Manager by the Project QA Officer.

8.2 Data Validation for Bench-Scale Testing

Data validation is an evaluation of the technical usability of the verified data with respect to the planned objectives of the project. Data validation is performed following data verification. Data validation consists of the following:

1. Determine and ensure that data provide necessary information to make decisions or address project objectives
2. Assign qualifiers to individual data values. The assigned qualifiers indicate the degree to which the data can be used when drawing conclusions based on the entire data set. Examples of data qualification may include :

    Analyte not detected above MDL
    Concentration of analyte is approximate due to interference
    Identification of analyte is uncertain due to interference
    Concentration of analyte is confirmed

3. Assess applicability of certain performance criteria (e.g., DQOs) used to make decisions on measured data, based on data gathered during the course of the Project. For instance, information on the magnitude of analytical error for a certain method may result in re-evaluation of precision criteria.
4. Determine whether DQOs were satisfied and whether data can proceed to Quality Assessment (Data Quality Assessment consists of reviewing DOQs and sampling design, preliminary data review, selecting statistical tests, verifying assumptions and hypotheses and drawing conclusions).

Data validation will be conducted by the Project QA Officer. In addition, all data gathered will be reviewed by Project QA Officer every quarter. If the data quality indicators do not meet the criteria outlined in the QAPP, data may be discarded or flagged with data qualifiers. Bench-scale test re-sampling or re-analysis may be conducted. If failure to meet DQOs is due to equipment failure, then calibration and maintenance of analytical instruments will be made more stringent. If failure to meet DQOs is due to inadequate expertise of sampling and analysis personnel, then they will be retrained in bench-scale testing methods.

8.3 Reconciliation with User Requirements

The principal investigators and the QA Officer will make decisions to either reject or qualify data based on criteria outlined in the Data Quality Objectives. (Also, see Corrective measures). Modifications may be warranted at various levels based on obtained results. Potential problems with data quality and any modifications to initial DQOs will be transmitted to the WERF Program Director via routinely held project conference calls.

Note on Data Verification and Validation: Based on results of data verification and validation, sampling and analysis may be repeated before achieving data that can successfully proceed to data assessment. If exhaustive corrective measures do not improve data quality, such data may not be used. However, if the requirements set forth in the QAPP are followed, most acquired data may be consistent with Project requirements and data rejection may be minimal.

9.0 ASSESSMENT AND OVERSIGHT

9.1 Assessments

Weekly meetings will be conducted at Columbia University to oversee the progress of the study, involving Prof. Kartik Chandran, Dr. Sungpyo Kim and Mr. Joon Ho Ahn. Monthly meetings involving the Project Managers, teams and the PSC will be conducted via conference calls to ensure efficient coordination between the activities at the sites around the country.

9.2 Reports to Management

The results of continuous monitoring of the full-scale reactors will be compiled within sixty days after a sampling event. Bench-scale monitoring reports will be submitted once a year following a review during the routine meetings held between the project team and the PSC.

9.3 Documentation and Records – Columbia University

A printed copy (MS Word®) of the most recently updated version of the QAPP will be present in the offices of the principal investigators. A printed master copy of the current QAPP will be maintained in a dedicated Binder in the Environmental Biotechnology Laboratory, Columbia University (Mudd Building, Room 1041) for ready reference to laboratory personnel. In addition, the Binder will contain hard copies of routinely generated calibration curves, audit reports, detailed standard operating procedures for each analytical method or instrument used in the Project and copies of Chain of Custody forms. Detailed records of sampling and analytical procedures and the measured results will be maintained in the laboratory notebooks of the respective laboratory personnel. Laboratories notebooks will be maintained per Kanare, 1985 (*2*). Difficulties encountered during sampling and analysis will be documented in the laboratory notebooks. Documented sampling and analysis problems will be discussed and resolved during monthly PSC conference calls. Problems during sampling and analysis may also be resolved by contacting the Project Quality Officer, if necessary. Additionally, the manufacturer of the equipment being used may be contacted directly.

9.4 Documentation and Records – Participating and TCR WWTP Facilities

Each participating or TCR facility will receive a printed copy (MS Word®) of the most recently updated version of the QAPP which they will retain in the offices of the principal contact during the period of performance of this study.

Each laboratory conducting the analysis of wastewater samples for conventional parameters will follow their Standard Operating Procedures for records retention. Given the significant implications of the data generated from this study in the development of gaseous nitrogen emission factors from the wastewater treatment industry, the data sets will be stored for as long as feasible in both hardcopy and electronic format. Each participating WWTP facility will turn over the wastewater characterization data to the Columbia University research team, including QC results collected during each sampling event.

10.0 REFERENCES

1. P. Tata, J. Witherspoon, C. Lue-Hing, Eds., *VOC Emissions from Wastewater Treatment Plants* (Lewis Publishers, Boca Raton, FL, 2003).

2. H. M. Kanare, *Writing the Laboratory Notebook* (American Chemical Society, Washington, D.C, 1985).

3. A. D. Eaton, L. S. Clesceri, A. E. Greenberg, Eds., *Standard methods for the examination of water and wastewater* (APHA, AWWA and WEF, Washington DC, ed. 21, 2005).

4. P. Nelson, *Introduction to EPA Test Methods. EPA Region I* (U.S. EPA, Boston, MA., 1998).

5. D. A. Skoog, D. M. West, F. J. Holler, *Fundamentals of Analytical Chemistry* (Saunders, New York, ed. 7th, 1996).

6. M. Kienbusch. (United States Environmental Protection Agency, 1986).

7. H. Melcer, "Methods for Wastewater Characterization in Activated Sludge Modelling" (Water Environment Research Foundation, 1999).

PROTOCOL FOR MEASURING THE SURFACE FLUX OF NITROUS OXIDE (N_2O) AND NITRIC OXIDE (NO) FROM ACTIVATED SLUDGE TANKS

Prepared by: K. Chandran
Last edit: K. Chandran July 22nd, 2008
Filename: GaseousNProtocol.doc

INTRODUCTION

The following protocol, which has been prepared as part of this project, is intended to provide utilities and field sampling teams with a detailed description of the data collection methodology and analysis requirements to enable calculation of gaseous nitrogen fluxes from different zones of activated sludge trains in a wastewater treatment facility.

EQUIPMENT, MATERIALS, and SUPPLIES NEEDED

1. Surface emission isolation flux chamber (commercially available from vendors, for instance, http://www.fivesenses.com/Prod_Emission.cfm or custom built based on specifications from the United States Environmental Protection Agency (*6*).
2. Teledyne API N_2O Monitor Model 320E (Teledyne API, San Diego, CA)
3. EcoPhysics NOx Analyzer Model CLD64 (EcoPhysics, Ann Arbor, MI)
4. Zero gas (containing zero ppm N_2O and NO), and N_2O and NO gas standards (Tech Air, White Plains, NY)
5. Dwyer series 475 Mark III digital manometers to measure flux chamber pressure from 0 to 1” (high sensitivity) and 0 to 100” (low sensitivity) of water column (Dwyer Instruments Inc., Michigan City, IN)
6. Rotameter to measure influent sweep gas flow rate, 0 - 30 L/min, (Fisher Scientific, Fairlawn, NJ)
7. Adjustable air pump, 0-10 L/min (Fisher Scientific, Fairlawn, NJ) to provide sweep gas flow into the flux chamber
8. Vacuum pump, 0-30 L/min (Fisher Scientific, Fairlawn, NJ) for active pumping of gas from the flux-chamber (never required based on sampling campaigns conducted to date)
9. 0.2 μm cartridge filters, set of 10 (Millipore, Ann Arbor, MI) to prevent fine particulates from entering the gas analyzers
10. Silica Gel column for capturing moisture (Fisher Scientific, Fairlawn, NJ)
11. Glass water trap consisting of a 100 ml glass bottle placed in ice within a Styrofoam® box
12. Teflon® tubing (approximately 0.5”) and fittings
13. 100-300’ extension cord and power strip
14. Laptop personal computer (with at least 512 MB RAM) with data acquisition programs for N_2O and NOx analyzers pre-installed
15. Set of miscellaneous hand-tools including adjustable wrenches, different size screw drivers and adjustable pliers.

EXPERIMENTAL PROCEDURE

The overall procedure for measuring N_2O, NO and NO_2 fluxes from the head-space of activated sludge tanks involves a variant of the EPA/600/8-86/008 and the SCAQMD tracer methods, which allow sampling of gaseous emissions from high surface flux rate operations.

Commercially available replicas of the United States Environmental Protection Agency surface emission isolation flux chamber (SEIFC) will be used to measure gaseous N fluxes from activated sludge reactors. The USEPA SEIFC essentially consists of a floating enclosed space through which, carrier gas (typically nitrogen or argon) is fed at a fixed flow rate and exhaust gas is collected in a real-time or discrete fashion. Since the surface area under the SEIFC can be calculated or measured, the specific flux of the gaseous compound of interest can thus be determined. Since the SEIFC ‘floats’ on the activated sludge tank surface, several replicate measurements can be taken at different locations in a single tank as well as from different tanks (nitrification, denitrification) along a treatment train. The SEIFC is also equipped with mixing (physical mixer or via sweep gas circulation) to ensure adequate gas and in some cases, an online temperature probe. The SEIFC is currently one of the few devices accepted by the U.S. EPA for measuring gaseous fluxes (*1*) and as such will be employed for this study.

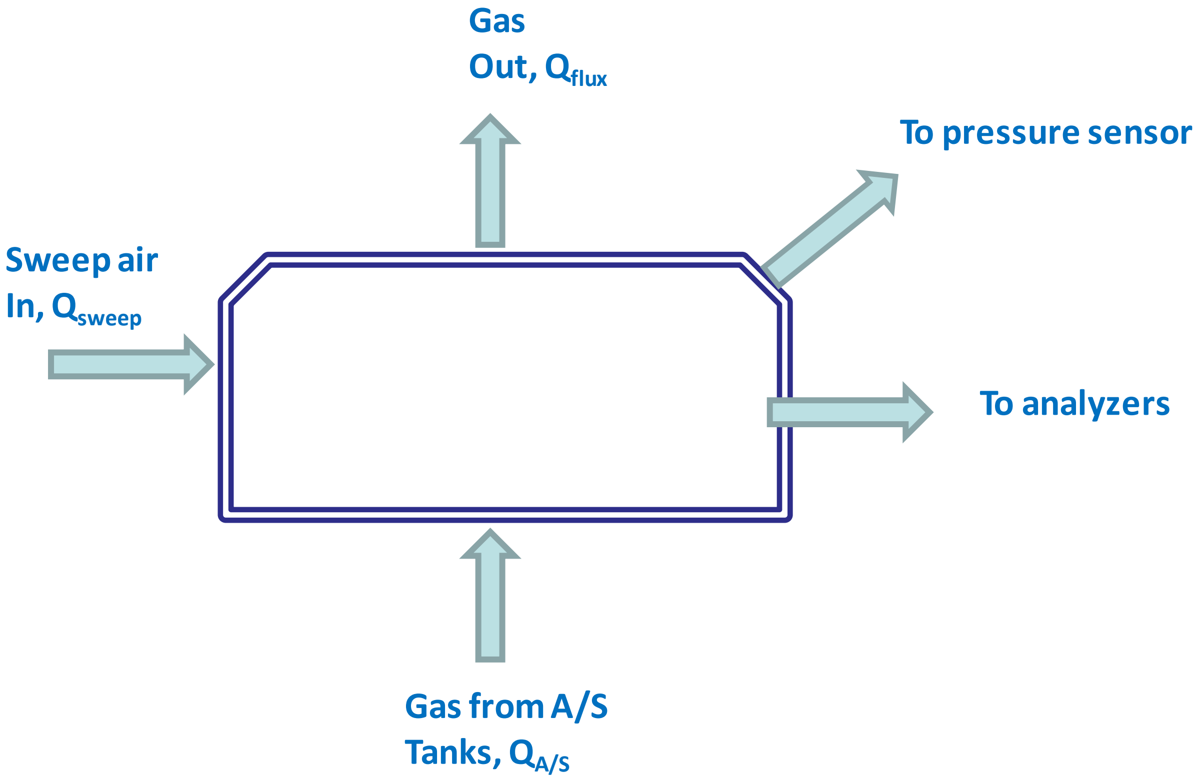


Figure A-4. Full-scale measurement of nitrogen gases will be done using the U.S. EPA surface emission isolation flux chamber (modified from (*1*)).

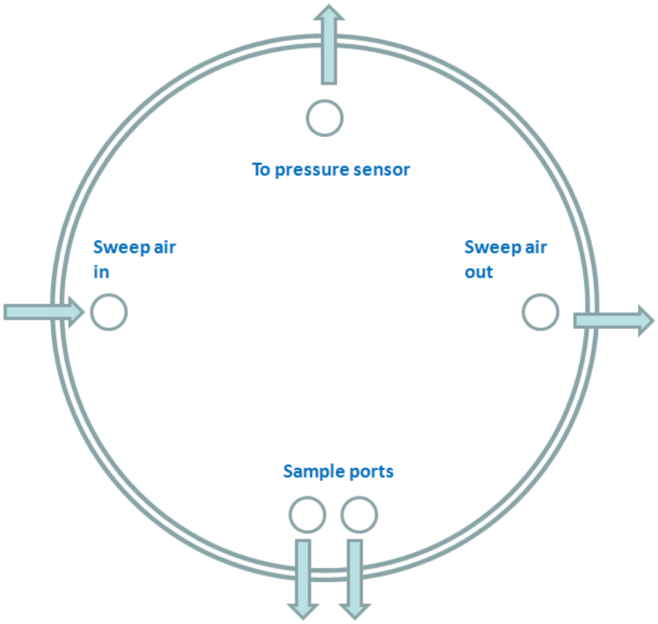


Figure A-5. Modified schematic of the flux chamber.

In general, sampling will be conducted at multiple locations of the activated sludge train in each wastewater treatment facility. These locations the aerobic, anoxic and anaerobic zones, depending upon the configuration of the given facility. Additionally, within each zone, multiple points (approximately three, but not less than two) will be sampled to address any variability in gas fluxes that may result due to variations in mixing or flow patterns therein.

Pressure build up can be minimized by equipping the flux chamber with multiple vents or a variable size vent and continuously monitoring the pressure drop across the hood using a sensitive pressure gauge. In this study, the latter approach (pressure gauge) will be followed to monitor the pressure across the flux chamber. In all field locations, gas flow rate will be measured using the tracer gas technique and pressure will be passively monitored if necessary. Alternately, the aeration rate from plant records (available as a order of magnitude verification)have also been used to estimate VOC fluxes from aeration tanks and a similar approach could be used in this study (Dr. Chuck Schmidt, personal communication). The modified set up of the flux chamber used in this study is depicted in Figures A4 through A6.

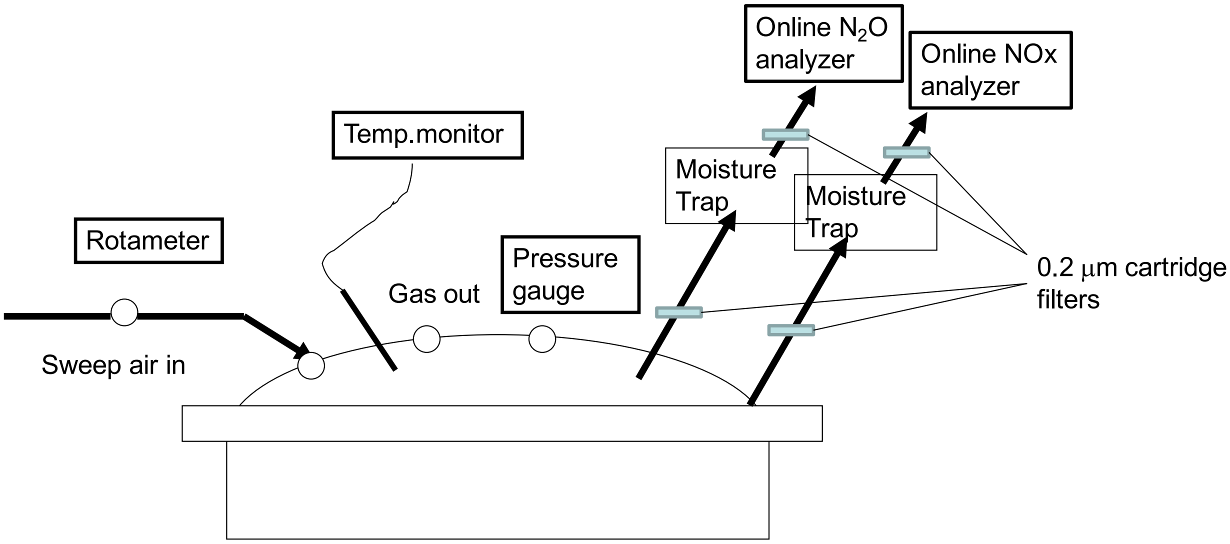


Figure A-6. Schematic of flux-chamber set-up for N_2 and NOx flux measurements.

Gas Phase Sampling Method in Aerobic Zones

1. Seal all but one vent in the flux chamber and connect high sensitivity pressure gauge to the one open vent.
2. Lower flux chamber into aerobic zone (bottom of rim should be below the surface of the water by 1-2 inches minimum).
3. Wait for N_2O analyzer to equilibrate based on stability indicator (<0.03)
4. Pull the flux chamber up. Open two vents and connect the N_2O analyzer, NOx analyzer. The other vents should be left open to atmosphere.
5. Record temperature of the gas in the flux chamber using a digital temperature gauge (Fisher Scientific number 15-077-8 or suitable alternate)
6. Care must be taken not to have the flow going to the two analyzers exceed the gas-flow rate from the flux-chamber. Otherwise, atmospheric air will be drawn in through the vents in the flux chamber.

Gas Phase Sampling Method in Anoxic Zones

1. Seal all but one vent in the flux chamber and connect high sensitivity pressure gauge to the one open vent.
2. Lower flux chamber into anoxic zone with a (1-2 inch minimum submergence, into the liquid surface)
3. Wait for N2O analyzer to equilibrate based on stability indicator (<0.03)
4. Pull the flux chamber up. Open two vents and connect the N_2O analyzer, NOx analyzer and the **sweep gas pump** (**Note: sweep gas only used during anoxic zone sampling)**. The other vents should be left open to atmosphere.
5. Record temperature of the gas in the flux chamber using a digital temperature gauge (Fisher Scientific number 15-077-8 or suitable alternate).
6. Care must be taken never to have the flow going to the two analyzers exceed the sweep gas rate or dilution air will be drawn in through an opening in the chamber.

Figure A-7 summarizes the data recording requirement checklist that needs to be followed for flux-chamber set up and operation. Additional analytes can be added by sampling teams based on a case specific basis.

Measurement	**Sampling Location 1**	**Sampling Location 2**	**Sampling Location 3**
Pressure in flux chamber			
Gas flow rate from flux chamber			
Gas temperature in flux chamber			
Wastewater temperature			
Air-pump flow rates			

Figure A-7. Checklist for flux-chamber set-up and operation in field.

Continuous and Real-Time N_2O Measurement

Measurement

1. Turn on the power by pressing the on/off switch on the front panel. The display should turn on and green (sample) status LED should be energized. The green LED should blink indicating the instrument has entered the HOLD-OFF mode. Sample mode can be entered immediately by pressing the EXIT button on the front panel. The red "fault" light will also be on until the flows, temperatures and voltages are within operating limits. Clear the fault messages. After the warm-up, review the TEST function values in the front panel display by pushing the left most keyboard button labeled TEST.
2. Activate the DAS data acquisition software and set the sampling frequency for 1 sample per minute.
3. Start data acquisition.
4. Connect the inlet tubing of the analyzer to the outlet tubing from the SEIFC securely using a standard 1/4” compression fitting connector.
5. Acquire data for about 20 min in anoxic zones and about 10 min in aerobic zones **after** stable readings are obtained- as indicated by the stability indicator on the N_2O analyzer.
6. Terminate the DAS software and immediately save the acquired data.
7. Repeat steps 2-5 for each sampling point and sampling locations (individual tanks).

Measurement Range

0-1000 ppm

Calibration

Before each sampling event, the instrument will be calibrated using “zero gas” and N_2O standard gas as per manufacturer’s instructions

Continuous and Real-Time NO and NO_2 Measurement

Measurement

1. Turn on the power by pressing the Power switch on the front panel and the external vacuum pump and wait till the display reads "**MEAS**" (this should typically take less than thirty minutes).
2. Activate the CLD data acquisition software and set the sampling and data save frequency for 1 sample per minute and 10 minutes, respectively. Start data acquisition.
3. Connect the inlet tubing of the analyzer to the outlet tubing from the SEIFC securely using a standard 1/4" compression fitting connector.
4. Acquire data for about 20 min in anoxic zones and about 10 min in aerobic zones **after** stable readings are obtained- as indicated by the stability indicator on the N_2O analyzer.
5. Terminate the CLD software and immediately save the acquired data.
6. Repeat steps 2-5 for each sampling point and sampling locations (individual tanks).

Measurement Range

Adjustable, 0-100 ppm

Calibration

Before each sampling event, the instrument will be calibrated using "zero gas" and NO standard gas as per manufacturer's instructions

Principles of Real-Time N_2O, NO and NO_2 Measurements

Principles of N_2O Measurement

Continuous N_2O measurements will be performed via infra-red (IR) gas-filter correlation, which is based on the absorption of IR radiation by N_2O molecules at wavelengths near 4.5 μm. As part of the measurement process, a broad wavelength IR beam is generated inside the instrument and passed through a rotating Gas Filter Wheel, which causes the beam to alternately pass through a gas cell filled with Nitrogen, (Measure Cell) and a cell filled with N_2O/N_2 Mixture (Reference Cell) at a frequency of 30cycles/sec. N_2O concentrations are inferred based on the amount of IR absorption at wavelengths close of 4.5 μm. Ultimately, the 'stripped' beam strikes the detector which is a thermoelectrically cooled solid-state photo-conductor. This detector, along with its pre-amplifier converts the light signal into a modulated voltage signal.

Principles of NO and NO_2 Measurement

The chemiluminescence approach is based on the gas-phase reaction of NO with excess ozone (O_3), which produces a characteristic near-infrared luminescence (broad-band radiation from 500 to 3,000 nm, with a maximum intensity at approximately 1,100 nm) with an intensity that is proportional to the concentration of NO. **It should be noted that this is the same reaction via which NO causes the depletion of the ozone layer.**

<u>Reaction chemistry involved in measurement of NO concentrations</u>

1. **$NO + O_3 \rightarrow NO_2 + NO_2^* O_2$** **Formation of stable and excited NO_2 by reaction of NO with O_3**

2. **NO_2^* ➔ $NO_2 + h\nu$** **Conversion of excited NO_2 to stable NO_2 with release of luminescent radiation**

Reaction chemistry involved in measurement of NO_2 concentrations

3. **NO_2 + reducing agent ➔ NO + oxidized reducing agent** **Reduction of NO_2 to NO**
4. **NO measurement by chemiluminescence (Reactions 1 and 2)**

To determine the concentration of NO by chemiluminescence, the sample gas flow from the nitrifying reactors is mixed with O_3 in a reaction chamber operated under negative pressure (vacuum). The chemiluminescence that results from these reactions is monitored by an optically filtered high sensitivity photomultiplier, that responds to NO_2 chemiluminescence emission at wavelengths longer than 600 nm. The electronic signal produced in the photomultiplier is proportional to the NO concentration in the sample gas. Measurement of NO_2 is achieved by means of a heated converter that reduces NO_2 to NO.

PROTOCOL FOR MEASURING LIQUID-PHASE NITROUS OXIDE

Prepared by: J-H. Ahn
Last edit: K. Chandran November 8th, 2008
Filename: Liquid Phase N_2O Protocol.doc

EQUIPMENT NEEDED

1. Nitrous Oxide Microsensor N2O25 (Unisense, Aarhus, Denmark)
2. 2 Channel picoammeter PA2000 (Unisense, Aarhus, Denmark)
3. Calibration Chamber CAL300 (Unisense, Aarhus, Denmark)
4. Zero air and N_2O gas standard (Tech Air, White Plains, NY)
5. Teflon® tubing, Silicone tubing and fittings
6. Squeezer with deionized water
7. Kimwipes
8. BD Falcon 50 ml conical tubes

EXPERIMENTAL PROCEDURE

Principles

The Unisense nitrous oxide microsensor is a miniaturized Clark-type sensor with an internal reference and a guard cathode. In addition, the sensor is equipped with an oxygen front guard, which prevents oxygen from interfering with the nitrous oxide measurements. The sensor is connected to a high-sensitivity picoammeter and the cathode is polarized against the internal reference. Driven by the external partial pressure, nitrous oxide from the environment will penetrate through the sensor tip membranes and be reduced at the metal cathode surface. The picoammeter converts the resulting reduction current to a signal. The internal guard cathode is also polarized and scavenges oxygen in the electrolyte, thus minimizing zero-current and pre-polarization time.

Measurement Steps

1. Turn on the power switch located on the front panel of picoammeter.
2. Check the ‘Gain’ screw for channel 1 is turned fully counter-clockwise.
3. Turn the display switch, located on the center of the panel, to ‘Signal 1’ and check that the display reads zero. If not, adjust the offset, as per the manufacturer’s instructions.
4. Turn the display switch to ‘Pol. 1’. Check if the polarization voltage shows -0.8 V. If not, adjust volt and polarity switch.
5. Connect the “pre-polarized” microsensor leads to the meter in the following order: (1) Signal wire (black) to ‘Input’ of channel 1 on the front panel. (2) Guard wire (yellow) to ‘Guard’ of channel 1.
6. Rinse out the sensor with deionized water and absorb the moisture with kimwipes.
7. Place the sensor into the calibration chamber which contains deionized water.
8. Select the ‘Normal’ setting for the ‘Mode’ switch on the front panel, unless you need the extremely fast response.

9. Select the appropriate measuring range using the ‘Range’ switch on the panel. Usually 200 pA is selected, but if not suitable, select an alternate range available.
10. Withdraw about 20 ml sample from test reactors in 50 ml conical centrifuge tubes or alternate similar containers (plastic or glass beakers are acceptable).
11. Take out the microsensor from the calibration chamber (containing deionized water), rinse out with deionized water, and mop dry with a tissue.
12. Immerse the microsensor into the samples. **For (10) and (12), proceed rapidly as possible after acquiring the sample**.
13. Record the numbers from the display on the picoammeter. The measurement numbers should be stable within one minute.
14. Pull out the microsensor, rinse out and place it back into the calibration chamber.
15. Repeat (x) ~ (xiv) for each sampling point and location.
16. When the measurements are complete, disconnect the sensor leads in the reverse order to which they were connected.

Measurement Range

Adjustable, 0- 0.616 ppmv-N_2O (with 500 ppm N_2O gas standard)

Pre-polarization Steps

If the sensor is new or has not been operated for several days, then it must be polarized for at least 2 hours and up to 12 hours before it can be calibrated and/or used.

1. Secure the nitrous oxide sensor with its tip, immersed in nitrous oxide free water.
2. Turn the display switch to ‘Pol.1’ and adjust the polarization to -1.30 V.
3. Turn the display switch to ‘Signal 1’ and adjust the ‘Gain’ screw completely counter-clockwise. Adjust the display to zero on the ‘Offset’ dial, if needed.
4. Connect the signal wire (black) of the microsensor to ‘Input’ terminal.
5. After 5 minutes, adjust the polarization to -0.8 V and then connect the guard wire (yellow) to ‘Guard’ terminal.
6. Prepolarize for as possible up to 12 hours to get the maximum stability.

Calibration

After the sensor has been polarized, it must be calibrated with zero air and N_2O gas standards. Typically, we have used 500 ppm N_2O gas standards for calibration. **Note 1:** N_2O gas standards are specialty items and can be purchased from vendors such as TechAir.

Note 2: To be consistent in terms of units for liquid and gas phase N_2O, the results of this study are expressed in terms of N_2O. Alternately, liquid and gas phase N_2O concentrations can also be expressed as “N” to estimate the fraction of influent nitrogen discharged as N_2O.

PROTOCOL FOR MEASURING EMISSION GAS FLOWRATE USING HELIUM TRACER GAS METHOD (after ASTM Method D1946)

Prepared by: S. Kim
Reviewed by: D. Katehis, M. Ward, K. Chandran
Last edit: K. Chandran January 14th, 2009
Filename: He Tracer Protocol.doc

In Aerated or Aerobic Zones

1. Activate the field gas-chromatograph approximately prior to the actual helium (He) measurements to allow for the thermal conductivity detector (TCD) and GC column to attain the desired temperatures.
2. After measuring gas-phase N_2O and NOx, disconnect the N_2O and NOx analyzers and connect one outlet vent to the inlet line of the field GC. Close the other vent.
3. Introduce tracer gas (10% He, 90% zero air) through an inlet vent into the flux chamber at a known flow rate (for instance 1L/min).
4. Measure the concentration of He gas exiting the flux chamber (as per ASTM method D1946).
5. Based on the measured He concentrations, calculate via linear algebra the flow rate of aeration tank headspace gas entering the flux chamber (equation 1).

$$Q_{tracer} * C_{helium-tracer} = (Q_{tracer} + Q_{emission}) * C_{helium-GC}$$

$$Q_{emission} = \frac{Q_{tracer} * (C_{helium-tracer} - C_{helium-GC})}{C_{helium-GC}} \qquad (1)$$

6. For each sampling location, conduct steps 2-5 at least three times

In Un-Aerated or Anoxic Zones

1. The only modification to the protocol for adaptation to measuring the emission flow rate from anoxic zones is the introduction of sweep gas.
2. Introduce sweep gas to the chamber at a flow rate of 4L/min and wait 6 min for steady-state.
3. Follow steps 2-6 as described above for determination of emission flow rate from aerobic zones.
4. Calculate the emission flow rate from the anoxic zone using equation 2

$$Q_{tracer} * C_{helium-tracer} = (Q_{tracer} + Q_{sweep} + Q_{emission}) * C_{helium-GC}$$

$$Q_{emission} = \frac{Q_{tracer} * (C_{helium-tracer} - C_{helium-GC})}{C_{helium-GC}} - Q_{sweep} \qquad (2)$$

Note: Each sampling campaign consists of discrete and continuous N_2O measurements. During the discrete N_2O measurements, $Q_{emission}$ will be determined at each location in the treatment plant where N_2O is measured. During continuous N_2O measurements, $Q_{emission}$ will be determined several times a day in correspondence with liquid-phase measurements.

DATA ANALYSIS AND PROCESSING

Liquid-phase Sampling in Aerobic and Anoxic Zones

Preliminary Data Gathering and Steady State Process Analysis. The integral dependence of N_2O and NO emissions on the process operating conditions make the development of a steady state analysis crucial. The following background information will need to be collected from candidate evaluation sites:

Overall Plant Description. Obtain general treatment plant configuration, liquid and solids process flow diagrams, design criteria, major mechanical process equipment, etc from the plant's design reports and/or O&M manuals. In addition, gather the following secondary process operating data:

- Secondary Process Configuration, including: Zone Configuration, operating set points, basins in services, aeration system (equipment, controls, monitoring capabilities), typical range of aeration rates, mixers (types, location, HP)
- Plant Operating Data. Summary of a minimum of three months plant data applicable to the treatment process to allow for characterization of the process influent, target and actual operating setpoints for key operational parameters (DO, SRT), effluent concentrations. Table A-7 provides an outline of typical data requirements.

Analyze the data collected using conventional techniques such as development of solids and nitrogen balances as well as through the use of the secondary process model. For the sake of brevity, details of model based evaluation are not presented in their entirety, since we expect to largely follow the procedure described in (*7*).

Intensive On-Site Sampling and Analysis

For facilities that are selected to participate an initial diurnal sampling effort will be conducted to characterize influent flow, organics and nitrogen concentrations to the facility, in preparation for the detailed liquid and air measurement campaign. For the initial diurnal sampling conventional parameters will be monitored from the secondary process as detailed in Table A-8, including:

- Influent Flowrate (minimum of once per hour)
- Influent and Effluent Ammonia (8 times per day)
- Influent and Effluent Nitrite & Nitrate (8 times per day, may substitute ($NO_2^- + NO_3^-$) with subset NO_2^-N measurement)
- Influent and Effluent COD (assume once per hour, can be reduced depending on site)

Additionally, the following diurnal performance and in-tank profiles will be gathered according to Table A-8.

Table A-7. Data Requirements for Plant Screening.

Sample Location	Analyte												
	TSS	VSS	Total cBOD$_5$[1]	Sol. cBOD$_5$	Total COD[1]	Sol. COD **0.45u**	ff COD	Temp	TKN[1]	Sol. TKN **0.45u**	NH3-N **0.45u**	NO3-N	NO2-N
Primary Effluent	1/wk	1/wk	1/wk	1/wk	1/wk	1/wk	1/wk		1/wk	1/wk	1/wk	1/wk	1/wk
Secondary Effluent	1/wk	1/wk	1/wk	1/wk	1/wk	1/wk[2]	1/wk[2]		1/wk	1/wk	1/wk	1/wk	1/wk
Reactor MLSS	1/wk	1/wk						1/wk					
RAS MLSS	1/wk												
WAS MLSS	1/wk[3]												
Clarifier	Blanket TSS (use sludge judge- 1/day and average once per week)												
Flow split and flow rate	**Different measurements possible** • Approximate- set PE gate and allow natural hydraulics (no info on range) • Confirm flow split by doing mass balance and MLSS concentrations • Alternately: take a measurement of MLSS at each pass: • Use Royce meter to get each pass TSS every 2-3 hours to get running average												
Anoxic Zone Mixing	Mechanical or aerator driven												
Operating Data													
Influent Flow	Diurnal Flow Pattern at Appropriate Time Intervals (15 minutes for periods of rapid diurnal increase, 1 hour for stable periods)												
RAS Flow	Average weekly RAS Flow, Indicate location and type of flow measurement and variability of flow												
WAS Flow	Average weekly WAS Flow, Indicate location and type of flow measurement, times of WAS wasting if not continuous												
Dissolved Oxygen	1/day (then average weekly), indicate location of DO measurement along basin length and time of measurement												
Aeration Rate	Daily average, indicate location of Air Flow Measurement and variability over the course of the day. SCADA output at short time intervals would be best												
Pickle Liquor Consumption	Daily, indicate Ferric Chloride equivalent strength, dosing points and dose at each point												

[1] Homogenize subsample prior to "total" measurement. Discard remaining sample – **DO NOT** use for "filtrate" or "soluble" determinations

[2]: soluble COD can be used instead of ffCOD on the secondary effluent

[3]: when RAS and WAS are from the same stream, TSS measurement on one of these streams is sufficient

Table A-8. Data Requirements for Model Calibration.

Sample Location	Analyte													
	TSS	VSS	Total $cBOD_5$[1]	Soluble $cBOD_5$	Total COD[1]	Sol. COD	ff COD	TKN[1]	Sol. TKN	pH	Alk	NH3-N	NO3-N	NO2-N
Primary Effluent	8/d	2/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d
Secondary Effluent	8/d	-	8/d	8/d	8/d	8/d[2]	8/d[2]	8/d	8/d	8/d	8/d	8/d	8/d	8/d
RAS MLSS	8/d													
WAS MLSS	8/d[3]													
Operating Data														
Influent Flow	Diurnal Flow Pattern at Appropriate Time Intervals (15 minutes for periods of rapid diurnal increase, 1 hour for stable periods)													
RAS Flow	Average Daily RAS Flow, Indicate location and type of flow measurement and variability of flow													
WAS Flow	Average Daily WAS Flow, Indicate location and type of flow measurement, times of WAS wasting if not continuous													
Dissolved Oxygen	1/hr, indicate location of DO measurement along basin length and time of measurement													
Aeration Rate	Daily average, indicate location of Air Flow Measurement and variability over the course of the day. SCADA output at short time intervals would be best													
In-tank Profiles	TSS	VSS	pH	DO	ORP	Temp.	ff COD	Alk.	NH3-N	NO3-N	NO2-N			
	8/d	2/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d	8/d			

Determination of Fluxes

Calculate the net flux of gaseous N species (mg/min-m^2) based on the gas flow rate out of the flux chamber ($Q_{emission}$, L/min), gas concentration (parts per million) and the cross-sectional area of the SEIFC (m^2) (Equation 3).

$$\mathrm{Flux} = \frac{Q_{\mathrm{emission}} * C}{A} \qquad (3)$$

Correct the calculated flux reflect standard temperature (20°C) and pressure (1 atm.).

Determination of Lumped Emission Factors

Lumped N_2O emission factors for each facility will be computed based on the measured flux from each zone in the facility normalized to the daily influent total Kjeldahl nitrogen (TKN) loading (mass/mass) according to equation 4.

$$\mathrm{Emission-factor} = \frac{\sum_{i=1}^{n} \mathrm{Flux}_i * \mathrm{Area}_i - (\mathrm{kg}-\mathrm{N_2O}-\mathrm{N})}{\mathrm{Daily-inf\,luent-TKN-load-(kg-N)}} \qquad (4)$$

Where:

Flux_i = N_2O emission flux calculated from the i^{th} zone (kg N_2O-N/m^2-d)
Area_i = Surface area of the i^{th} zone (m^2)
n = number of zones in a given facility from which N_2O fluxes are captured

It should be noted that the above calculations reflect the emission factor calculated from discrete N_2O measurements. In plants where significant diurnal variability exists, such variability will be accounted for by a combination of explicit measurements in select zones and mathematical modeling output of N_2O fluxes from remaining zones.

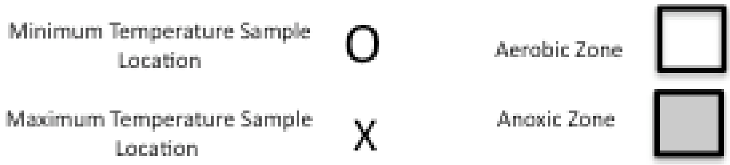
APPENDIX B

DATA FILES

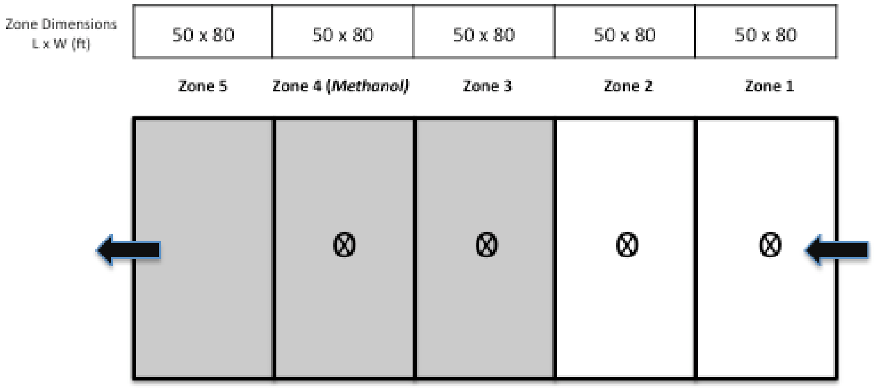
(Available on CD Rom by Request)

APPENDIX C

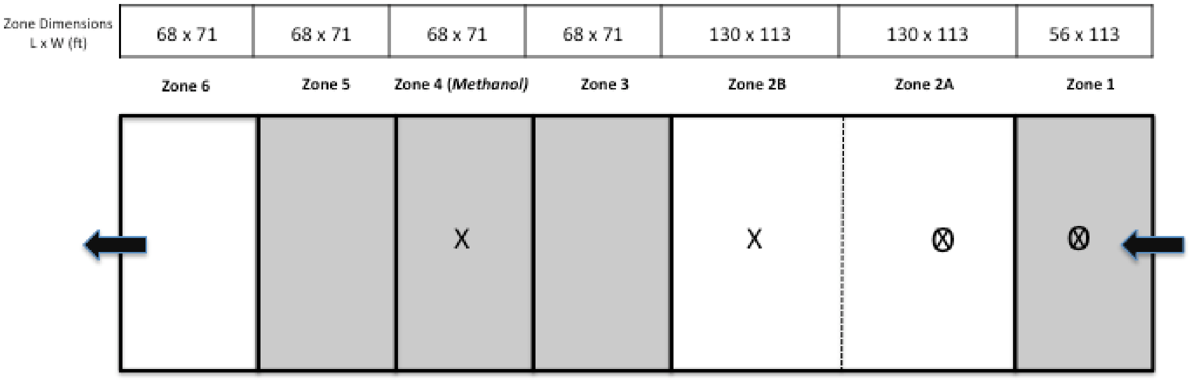
PROCESS SCHEMATICS OF WWTPS SAMPLED



Separate-stage BNR



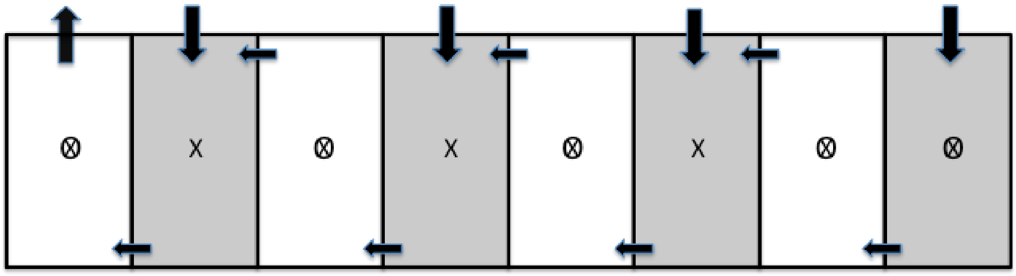
Four-stage Bardenpho



Attachment B

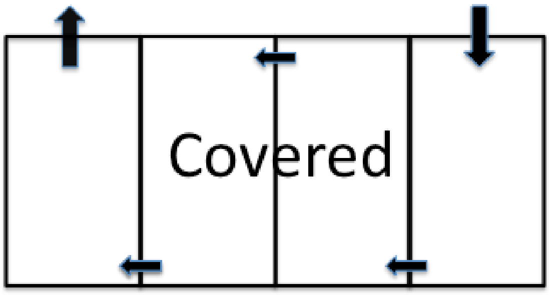
Step-feed BNR 1

	Pass D Zone 2	Pass D Zone 1	Pass C Zone 2	Pass C Zone 1	Pass B Zone 2	Pass B Zone 1	Pass A Zone 2	Pass A Zone 1
Zone Dimensions L x W (ft)	281 x 18	146 x 18	292 x 18	146 x 18	292 x 18	146 x 18	292 x 18	146 x 18



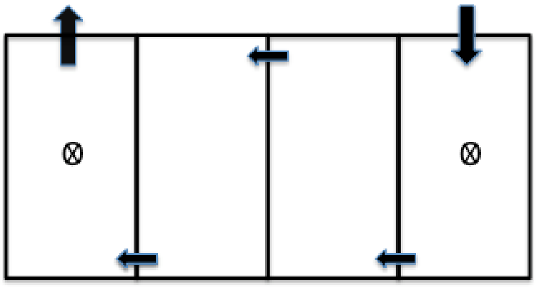
Step-feed non-BNR *

	Zone 4	Zone 3	Zone 2	Zone 1
Zone Dimensions L x W (ft)	385 x 21	385 x 21	385 x 21	385 x 21



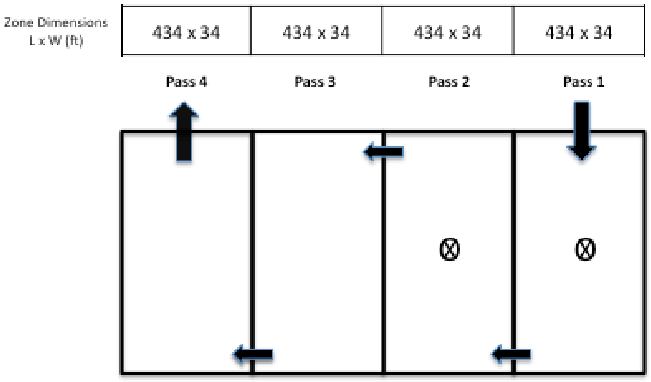
Separate centrate

	Pass D	Pass C	Pass B	Pass A
Zone Dimensions L x W (ft)	427 x 18	438 x 18	438 x 18	438 x 18

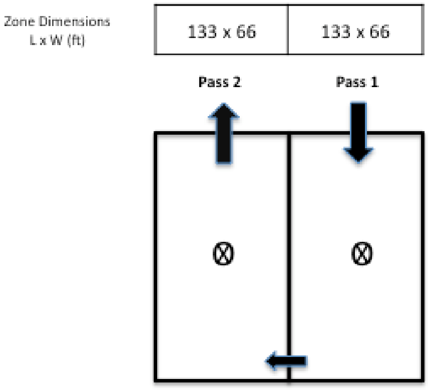


Attachment B

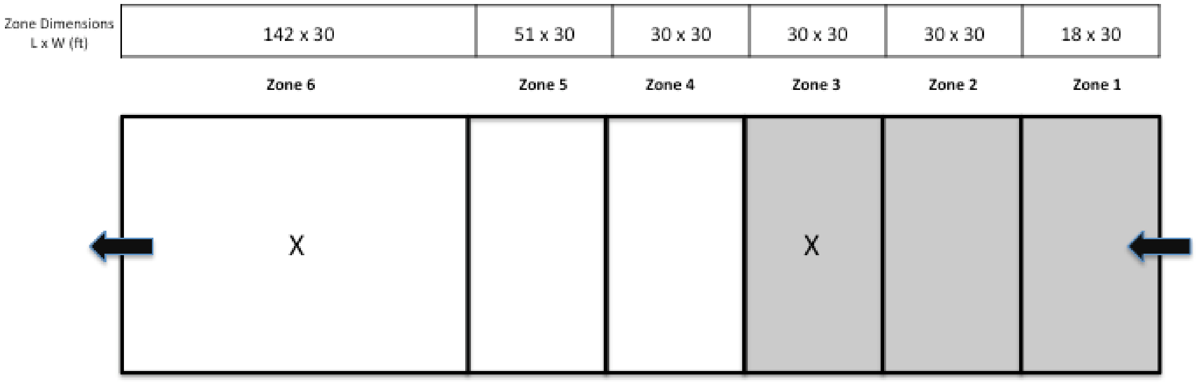
Plug flow 1



Plug flow 2

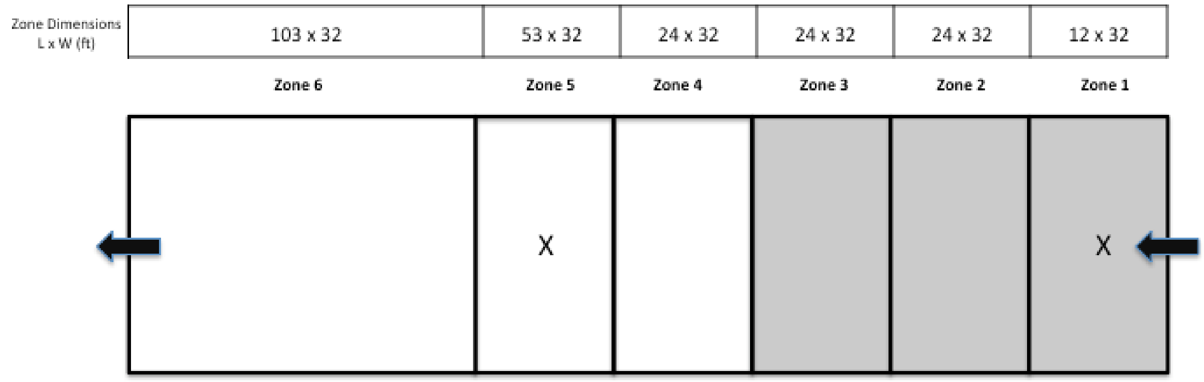


MLE 1

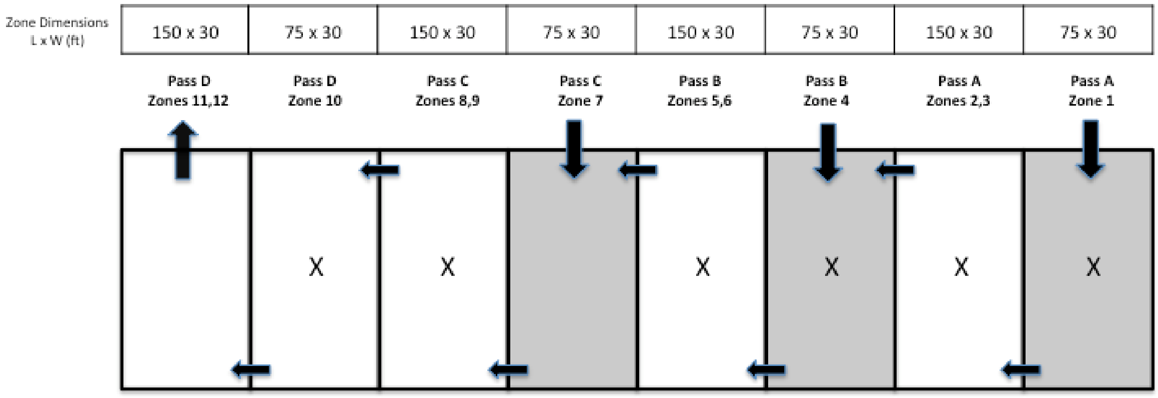


Attachment B

MLE 2

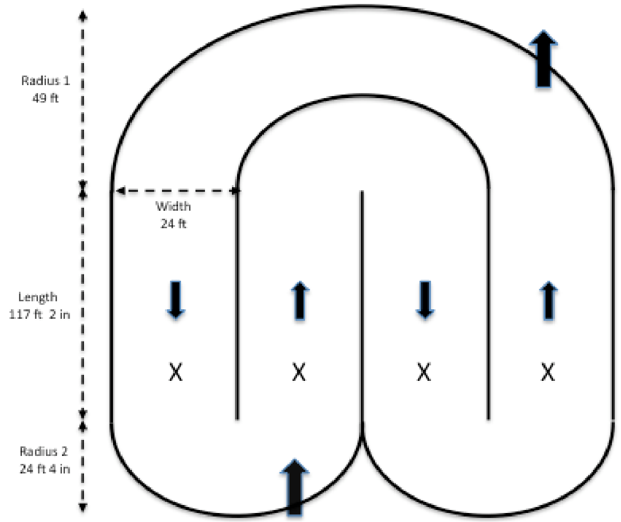


Step-feed BNR 2



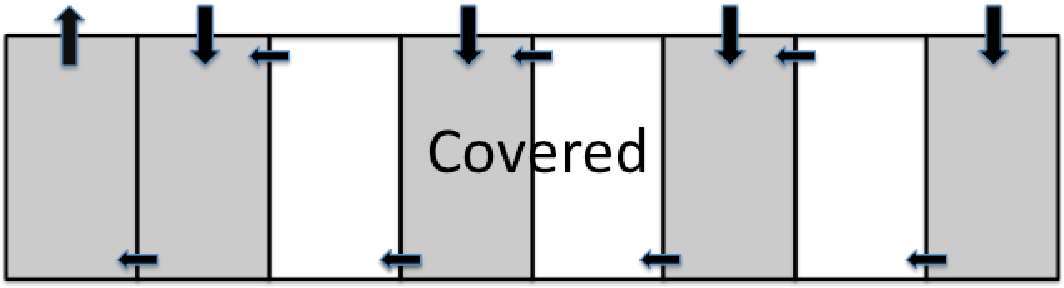
Oxidation ditch

Approximate Area (ft²)	4967	3742	3742	4967
	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**



Step-feed BNR 3*

Zone Dimensions L x W (ft)	360 x 43	160 x 43	360 x 43	160 x 43	360 x 43	160 x 43	360 x 43	160 x 43
	Pass D Zone 3	**Pass D Zones 1,2**	**Pass C Zone 3**	**Pass C Zones 1,2**	**Pass B Zone 3**	**Pass B Zones 1,2**	**Pass A Zone 3**	**Pass A Zones 1,2**



REFERENCES

Ahn, J.-H., Kim, S., Pagilla, K., Katehis, D., Chandran, K. (2009) Spatial and temporal variability in N_2O generation and emission from wastewater treatment plants. Nutrient Removal Conference. Washington D.C., Water Environment Federation.

Ahn, J.H., Kim, S., Park, H., Rahm, B., Pagilla, K., Chandran, K. (2010) N2O Emissions from Activated Sludge Processes, 2008a-2009: Results of a National Monitoring Survey in the United States. Environ. Sci. Technol.

Anderson, I.C., Levine, J.S. (1986) Relative rates of nitric oxide and nitrous oxide production by nitrfiers, denitrifiers and nitrate respirers. Appl. Environ. Microbiol., 51, 938-945.

Anderson, I.C., Poth, M., Homstead, J., Burdige, D. (1993) A comparison of NO and N2O production by the autotrophic nitrifier Nitrosomonas europaea and the heterotrophic nitrifier Alcaligenes faecalis. Appl. Environ. Microbiol., 59, 3525-3533.

Arp, D.J., Stein, L.Y. (2003) Metabolism of Inorganic N Compounds by Ammonia-Oxidizing Bacteria. Crit. Rev. Biochem. Mol. Biol., 38, 471-495.

Baytshtok, V., Kim, S., Yu, R., Park, H., Chandran, K. (2008) Molecular and biokinetic characterization of methylotrophic denitrification using nitrate and nitrite as terminal electron acceptors. Water Sci. Technol., 58, 359-365.

Baytshtok, V., Lu, H., Park, H., Kim, S., Yu, R., Chandran, K. (2009) Impact of varying electron donors on the molecular microbial ecology and biokinetics of methylotrophic denitrifying bacteria. Biotechnol. Bioeng., 102, 1527-1536.

Beaumont, H.J.E., Hommes, N.G., Sayavedra-Soto, L.A., Arp, D.J., Arciero, D.M., Hooper, A.B., Westerhoff, H.V., Van Spanning, R.J.M. (2002) Nitrite Reductase of Nitrosomonas europaea Is Not Essential for Production of Gaseous Nitrogen Oxides and Confers Tolerance to Nitrite. J. Bacteriol., 184, 2557-2560.

Beaumont, H.J.E., Lens, S.I., Reijnders, W.N.M., Westerhoff, H.V., Van Spanning, R.J.M. (2004a) Expression of nitrite reductase in Nitrosomonas europaea involves NsrR, a novel nitrite-sensitive transcription repressor. Mol. Microbiol., 54, 148-158.

Beaumont, H.J.E., Lens, S.I., Westerhoff, H.V., Van Spanning, R J.M. (2005) Novel *nirK* cluster genes in *Nitrosomonas europaea* are required for NirK-dependent tolerance to nitrite. J. Bacteriol., 187, 6849-6851.

Beaumont, H.J.E., Van Schooten, B., Lens, S.I., Westerhoff, H.V., Van Spanning, R.J.M.

(2004b) Nitrosomonas europaea Expresses a Nitric Oxide Reductase during Nitrification. J. Bacteriol., 186, 4417-4421.

Betlach, M.R., Tiedje, J.M. (1981) Kinetic explanation for accumulation of nitrite, nitric oxide and nitrous oxide during bacterial denitrification. Appl. Environ. Microbiol., 42, 1074-1084.

Bock, E. (1995) Nitrogen loss caused by denitrifying Nitrosomonas cells using ammonium or hydrogen as electron donors and nitrite as electron acceptor. Arch. Microbiol., 163, 16-20.

Bollmann, A., Bar-Gilissen, M.-J., Laanbroek, H.J. (2002) Growth at Low Ammonium Concentrations and Starvation Response as Potential Factors Involved in Niche Differentiation among Ammonia-Oxidizing Bacteria. Appl. Environ. Microbiol., 68, 4751-4757.

Burgess, J.E., Stuetz, R.M., Morton, S., Stephenson, T. (2002) Dinitrogen oxide detection for process failure early warning systems. Water Sci. Technol., 45, 247–254.

Butler, M.D., Wang, Y.Y., Cartmell, E., Stephenson, T. (2009) Nitrous oxide emissions for early warning of biological nitrification failure in activated sludge. Wat. Res., 43, 1265-1272.

Chain, P., Lamerdin, J., Larimer, F., Regala, W., Lao, V., Land, M., Hauser, L., Hooper, A., Klotz, M., Norton, J., Sayavedra-Soto, L., Arciero, D., Hommes, N., Whittaker, M., Arp, D. (2003) Complete genome sequence of the ammonia-oxidizing bacterium and obligate chemolithoautotroph *Nitrosomonas europaea*. J. Bacteriol., 185, 2759-2773.

Chandran, K. (2009) Characterization of nitrogen greenhouse gas emissions from wastewater treatment BNR operations: Field protocol with quality assurance plan. Alexandria, VA, Water Environment Research Foundation.

Chandran, K., Love, N.G. (2008) Physiological state, growth mode, and oxidative stress play a role in Cd(II)-mediated inhibition of *Nitrosomonas europaea* 19718. Appl. Environ. Microbiol., 74, 2447-2453.

Chandran, K., Smets, B.F. (2008) Biokinetic characterization of the acceleration phase in autotrophic ammonia oxidation. Wat. Environ. Res., 80, 732-739.

Colliver, B.B., Stephenson, T. (2000) Production of nitrogen oxide and dinitrogen oxide by autotrophic nitrifiers. Biotechnology Advances, 18, 219-232.

Czepiel, P., Crill, P., Harriss, R. (1995) Nitrous Oxide Emissions from Municipal Wastewater Treatment. Environ. Sci. Technol., 29, 2352-2356.

Davidson, E.A., Matson, P.A., Vitousek, P.M., Riley, R., Dunkin, K., Garcia-Mendez, G., Maass, J.M. (1993) Processes Regulating Soil Emissions of NO and N^2O in a Seasonally

Dry Tropical Forest. Ecology, 74, 130-139.

Dean, J.A. (Ed.) (1985) Lange's Handbook of Chemistry, New York, NY, McGraw-Hill Book Company.

Eaton, A.D., Clesceri, L.S., Greenberg, A.E. (Eds.) (2005) Standard methods for the examination of water and wastewater, Washington, DC, APHA, AWWA and WEF.

Focht, D.D. (1974) The effect of temperature, pH and aeration on the production of nitrous oxide and gaseous nitrogen - A zero order kinetic model. Soil Sci., 118, 173-179.

Frear, D.S., Burrell, R.C. (1955) Spectrophotometric method for determining hydroxylamine reductase activity in higher plants. Analytical Chemistry, 27, 1664-1665.

Ginige, M.P., Hugenholtz, P., Daims, H., Wagner, M., Keller, J., Blackall, L.L. (2004) Use of Stable-Isotope Probing, Full-Cycle rRNA Analysis, and Fluorescence In Situ Hybridization-Microautoradiography To Study a Methanol-Fed Denitrifying Microbial Community. Appl. Environ. Microbiol., 70, 588-596.

Girsch, P., De Vries, S. (1997) Purification and initial kinetic and spectroscopic characterization of NO reductase from Paracoccus denitrificans. Biochimica et Biophysica Acta (BBA) - Bioenergetics, 1318, 202-216.

Goreau, T.J., Kaplan, W.A., Wofsy, S.C., Mcelroy, M.B., Valois, F.W., Watson, S.W. (1980) Production of NO2- and N2O by Nitrifying Bacteria at Reduced Concentrations of Oxygen. Appl. Environ. Microbiol., 40, 526-532.

Goretski, J., Zafiriou, O.C., Hollocher, T.C. (1990) Steady-state nitric oxide concentrations during denitrification. Journal of Biological Chemistry, 265, 11535-11538.

Grady, C.P.L.J., Daigger, G.T., Lim, H.C. (1999) Biological wastewater treatment., New York, Marcel Dekker.

Guisasola, A., Jubany, I., Baeza, J.A., Carrera, J., Lafuente, J. (2005) Respirometric estimation of the oxygen affinity constants for biological ammonium and nitrite oxidation. J. Chem. Technol. Biotechnol., 80, 388-396.

Hanaki, K., Hong, Z., Matsuo, T. (1992) Production of nitrous oxide gas during denitrification of wastewater. Water Sci. Technol., 26, 1027-1036.

Holmes, A.J., Costello, A., Lidstrom, M.E., Murrell, J.C. (1995) Evidence that particulate methane monooxygenase and ammonia monooxygenase may be evolutionarily related. FEMS Microbiol. Lett., 132, 203-208.

Hooper, A.B. (1969 (b)) Lag phase of ammonia oxidation by resting cells of *Nitrosomonas europaea.* J. Bacteriol., 97, 968-969.

Hooper, A.B., Vannelli, T., Bergmann, D.J., Arciero, D.M. (1997) Enzymology of the oxidation of ammonia to nitrite by bacteria. Antonie van Leeuwenhoek, 71, 59-67.

Jiang, Q.-Q., Bakken, L.R. (1999) Nitrous Oxide Production and Methane Oxidation by Different Ammonia-Oxidizing Bacteria. Appl. Environ. Microbiol., 65, 2679-2684.

Kampschreur, M.J., Tan, N.C.G., Kleerebezem, R., Picioreanu, C., Jetten, M.S.M., Loosdrecht, M.C.M.V. (2008a) Effect of Dynamic Process Conditions on Nitrogen Oxides Emission from a Nitrifying Culture. Environ. Sci. Technol., 42, 429-435.

Kampschreur, M.J., Van Der Star, W.R.L., Wielders, H.A., Mulder, J.W., Jetten, M.S.M., Van Loosdrecht, M. C. M. (2008b) Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment. Wat. Res., 42, 812-826.

Kester, R.A., De Boer, W., Laanbroek, H.J. (1997) Production of NO and N2O by pure cultures of nitrifying and denitrifying bacteria during changes in aeration. Appl. Environ. Microbiol., 63, 3872-3877.

Kimochi, Y., Inamori, Y., Mizuochi, M., Xu, K.-Q., Matsumura, M. (1998) Nitrogen removal and N2O emission in a full-scale domestic wastewater treatment plant with intermittent aeration. J. Ferment. Bioeng., 86, 202-206.

Knowles, R. (1982) Denitrification. Microbiol. Rev., 46, 43-70.

Korner, H., Zumft, W.G. (1989) Expression of denitrification enzymes in response to the dissolved oxygen level and respiratory substrate in continuous culture of *Pseudomonas stutzeri*. Appl. Environ. Microbiol., 55, 1670-1676.

Lu, H., Chandran, K. (2010) Factors promoting emissions of nitrous oxide and nitric oxide from denitrifying sequencing batch reactors operated with methanol and ethanol as electron donors. Biotechnol. Bioeng., 106, 390-398.

Madigan, M.T., Martinko, J.M. (2006) Brock Biology of Microorganisms, Upper Saddle River, NJ, Prentice Hall.

Moyer, C.L., Dobbs, F.C., Karl, D.M. (1994) Estimation of diversity and community structure through restriction fragment length polymorphism distribution analysis of bacterial 16S rRNA genes from a microbial mat at an active, hydrothermal vent system, Loihi Seamount, Hawaii. Appl. Environ. Microbiol., 60, 871-879.

Nadkarni, M.A., Martin, F.E., Jacques, N.A., Hunter, N. (2002) Determination of bacterial load by real-time PCR using a broad-range (universal) probe and primers set. Microbiol., 148, 257-266.

Okano, Y., Hristova, K.R., Leutenegger, C.M., Jackson, L.E., Denison, R.F., Gebreyesus, B., Lebauer, D., Scow, K.M. (2004) Application of real-time PCR to study effects of ammonium on population size of ammonia-oxidizing bacteria in soil. Appl. Environ. Microbiol., 70, 1008-1016.

Osaka, T., Ebie, Y., Tsuneda, S., Inamori, Y. (2008) Identification of the bacterial community involved in methane-dependent denitrification in activated sludge using DNA stable-isotope probing. FEMS Microbiol. Ecol., 64, 494-506.

Otte, S., Grobben, N.G., Robertson, L.A., Jetten, M.S., Kuenen, J.G. (1996) Nitrous oxide production by Alcaligenes faecalis under transient and dynamic aerobic and anaerobic conditions. Appl. Environ. Microbiol., 62, 2421-2426.

Park, K.Y., Inamori, Y., Mizuochi, M., Ahn, K.H. (2000) Emission and Control of Nitrous Oxide from a Biological Wastewater Treatment System with Intermittent Aeration. The Society for Biotechnology, Japan, 90, 247-252.

Poth, M. (1985) Dinitrogen production from nitrite by a *Nitrosomonas* isolate. Appl. Environ. Microbiol., 52, 957-959.

Poth, M., Focht, D.D. (1985) 15N Kinetic Analysis of N2O Production by Nitrosomonas europaea: an Examination of Nitrifier Denitrification. Appl. Environ. Microbiol., 49, 1134-1141.

Ravishankara, A.R., Daniel, J.S., Portmann, R.W. (2009) Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. Science, 1176985.

Ritchie, G.A.F., Nicholas, D.J.D. (1972) Identification of the sources of nitrous oxide produced by oxidative and reductive processes in Nitrosomonas europaea. Biochem. J., 126, 1181-1191.

Rittmann, B.E., Mccarty, P.L. (2001) Environmental Biotechnology_ Principles and Applications, New York, McGraw Hill.

Schmidt, I., Bock, E. (1997) Anaerobic ammonia oxidation with nitrogen dioxide by *Nitrosomonas eutropha*. Arch. Microbiol., 167, 106-111.

Schmidt, I., Bock, E. (1998) Anaerobic ammonia oxidation by cell-free extracts of Nitrosomonas eutropha. Antonie van Leeuwenhoek, 73, 271-278.

Schmidt, I., Van Spanning, R.J.M., Jetten, M.S.M. (2004) Denitrification and ammonia oxidation by *Nitrosomonas europaea* wild-type, and NirK- and NorB-deficient mutants. Microbiol., 150, 4107-4114.

Shaw, L.J., Nicol, G.W., Smith, Z., Fear, J., Prosser, J.I., Baggs, E.M. (2006) Nitrosospira spp. can produce nitrous oxide via a nitrifier denitrification pathway. Environ. Microbiol., 8, 214-222.

Sommer, J., Ciplak, A., Sumer, E., Benckiser, G., Ottow, J.C.G. (1998) Quantification of emitted and retained N2O in a municipal wastewater treatment plant with activated sludge and nitrification-denitrification units. Agrobiological Research, 51, 59-73.

Stuven, R., Vollmer, M., Bock, E. (1992) The impact of organic matter on nitric oxide formation by *Nitrosomonas europaea*. Arch. Microbiol., 158, 439-443.

Sümer, E., Weiske, A., Benckiser, G., Ottow, J.C.G. (1995) Influence of environmental conditions on the amount of N2O released from activated sludge in a domestic waste water treatment plant. Cell. Mol. Life Sci., 51, 419-422.

Sutka, R.L., Ostrom, N.E., Ostrom, P.H., Breznak, J.A., Gandhi, H., Pitt, A.J., Li, F. (2006) Distinguishing Nitrous Oxide Production from Nitrification and Denitrification on the Basis of Isotopomer Abundances. Appl. Environ. Microbiol., 72, 638-644.

Tallec, G., Garnier, J., Billen, G., Gousailles, M. (2006) Nitrous oxide emissions from secondary activated sludge in nitrifying conditions of urban wastewater treatment plants: Effect of oxygenation level. Wat. Res., 40, 2972-2980.

Tallec, G., Garnier, J., Billen, G., Gousailles, M. (2008) Nitrous oxide emissions from denitrifying activated sludge of urban wastewater treatment plants, under anoxia and low oxygenation. Bioresour. Technol., 99, 2200-2209.

Tata, P., Witherspoon, J., Lue-Hing, C. (Eds.) (2003) VOC Emissions from Wastewater Treatment Plants*,* Boca Raton, FL, Lewis Publishers.

Tchobanoglous, G., Burton, F.L., Stensel, H.D. (2003) Metcalf and Eddy Wastewater Engineering: Treatment and Reuse, New York, NY, McGraw Hill.

U.S. EPA (2009) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006, EPA 430-R-08-005. Washington, D.C.

Vadivelu, V.M., Keller, N., Yuan, Z. (2007) Free ammonia and free nitrous acid inhibition on the anabolic and catabolic processes of Nitrosomonas and Nitrobacter. Water Sci. Technol., 56, 89-97.

Von Schultess, R., Kuhni, M., Gujer, W. (1995) Release of nitric and nitrous oxides from denitrifying activated sludge. Wat. Res., 29, 215-226.

Von Schultess, R., Wild, D., Gujer, W. (1994) Nitric and nitrous oxides from denitrifying activated sludge at low oxygen concentration. Water Sci. Technol., 30, 123-132.

Wicht, H., Beier, M. (1995) N2O emission aus nitrifizierenden und denitrificierended Klaranlagen. Korrespondenz Abwasser, 42, 404-406, 411-413.

Wrage, N., Velthof, G.L., Laanbroek, H.J., Oenema, O. (2004) Nitrous oxide production in grassland soils: assessing the contribution of nitrifier denitrification. Soil Biology and Biochemistry, 36, 229-236.

Yu, R., Kampschreur, M.J., Loosdrecht, M.C.M.V., Chandran, K. (2010) Mechanisms and Specific Directionality of Autotrophic Nitrous Oxide and Nitric Oxide Generation during Transient Anoxia. Environ. Sci. Technol., 44, 1313-1319.

Zhou, Y., Pijuan, M., Zeng, R.J., Yuan, Z. (2008) Free Nitrous Acid Inhibition on Nitrous Oxide Reduction by a Denitrifying-Enhanced Biological Phosphorus Removal Sludge. Environ. Sci. Technol., 42, 8260-8265.

Zumft, W.G. (1992) The denitrifying prokaryotes. In Balows, A., H.G. Truper, M. Dworkin, W. Harder and K. H. Schleifer (Ed.) The Prokaryotes. 2nd ed. Berlin, Springer-Verlag.

Zumft, W.G. (1997) Cell biology and molecular basis of denitrification. Microbiol. Mol. Biol. Rev., 61, 533-616.

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FINAL REPORT

Evaluation of Greenhouse Gas Emissions from Septic Systems

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EVALUATION OF GREENHOUSE GAS EMISSIONS FROM SEPTIC SYSTEMS

by:

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2010

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ABSTRACT AND BENEFITS

Abstract:

This study determined the emission rates of greenhouse gases (GHGs) from individual onsite septic systems used for the management of domestic wastewater. A static flux chamber method was used to measure the emission rates of methane, carbon dioxide, and nitrous oxide gases from eight septic tanks and two soil dispersal systems. A technique developed for the measurement of gas flow and concentration at clean-out ports was used to determine the mass flow of gases moving through the household drainage and vent system. There was general agreement in the methane emission rates for the flux chamber and vent system methods. Several sources of variability in the emission rates were also identified.

The septic tank was the primary source of methane, whereas the soil dispersal system was the principal source of carbon dioxide and nitrous oxide emissions. Methane concentrations from the soil dispersal system were found to be near ambient concentrations, similarly negligible amounts of nitrous oxide were found in the septic tank. All emissions originating in the soil dispersal system were discharged through the building vent as a result of natural, wind-induced flow. The gaseous emission rate data were determined to be geometrically distributed. The geometric mean and standard deviation (s_g) of the total atmospheric emission rates for methane, carbon dioxide, and nitrous oxide based on samples from the vent system were estimated to be 10.7 ($s_g = 1.65$), 335 ($s_g = 2.13$), and 0.20 ($s_g = 3.62$) g/capita·d, respectively. The corresponding total anthropogenic CO_2 equivalence (CO_2e) of the GHG emissions to the atmosphere, is about 0.1 tonne CO_2e/capita·yr.

Benefits:

- Provides methods to determine the GHG emission rates from septic tanks, venting systems, and soil dispersal systems.
- Improves upon the estimation of GHG emission rates from septic tank systems.
- Provides the atmospheric emission rate values for future GHG inventories from septic tank systems in California.
- Examines the GHG generation pathways in typical septic tank system.
- Identifies sources of variability in the GHG emission rates that can be used as a basis for future studies.

Keywords: Onsite wastewater treatment system, anaerobic, flux chambers, greenhouse gases, methane, carbon dioxide, nitrous oxide, septic tank, vent system, soil dispersal system.

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AB	Assembly Bill
ALT	Auburn Lake Trails
BOD_u	Ultimate carbonaceous oxygen demand
COD	Chemical oxygen demand
ECD	Electron capture detector
FC	Flux chamber
FTIR	Fourier transform infrared
GC	Gas chromatograph
GDPUD	Georgetown Divide Public Utility District
GHG	Greenhouse gas
GWP	Global warming potential
HRT	Hydraulic residence time
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
MB	Mass balance
M_g	Geometric mean
mg/L	Milligrams per liter
OD	Oxygen demand
OLR	Organic loading rate
ppb	Parts per billion
ppm	Parts per million
SRB	Sulfate reducing bacteria
s_g	Geometric standard deviation
SRT	Solids retention time
TDLSS	Tunable diode laser spectroscopy
UASB	Upflow anaerobic sludge blanket
UPC	Uniform plumbing code
USDA	United States Department of Agriculture
U.S. EPA	United States Environmental Protection Agency
VFA	Volatile fatty acid
VSS	Volatile suspended solid
WWTP	Wastewater treatment plant

EXECUTIVE SUMMARY

Methane has been identified as a potent greenhouse gas (GHG), with an equivalent effect 25 times that of carbon dioxide (IPCC, 2007). Based on the IPCC methodology, the U.S. EPA (2009) has determined that a significant amount of the methane emissions associated with wastewater originate from onsite septic tank systems due to the large number of individual septic systems now in use and the high methane emission rates predicted using the IPCC method. However, the actual data currently available on the emission of methane from septic tank systems are insufficient to produce an accurate greenhouse gas inventory for these systems. Thus, the principal objective of this research was to obtain more accurate data on GHG emissions from conventional septic tank systems, with a focus on methane emissions. To accomplish the objective, this project consisted of a literature review, construction of flux chambers, development of sampling techniques and protocols for gas sampling from septic tank system and ventilation systems, identification and selection of field sites, collection of gas samples, data analysis, and estimation of the GHG emission rate values.

Methodology

For this study, flux chambers and a corresponding sampling methodology were used to measure the GHG emission rates from conventional septic tank systems. The flux chamber method was also used for gas sampling of soil dispersal systems. In addition, a sampling device and methodology were developed to measure the mass flow of GHGs through drainage and ventilation systems. Based on the flux chamber and vent sampling data, emission rates of methane, carbon dioxide, and nitrous oxide from septic tank systems were estimated.

Results

In total, eight septic tanks were sampled for the production of gases from the tank contents using flux chambers. While methane production is attributed to anaerobic reactions occurring primarily in the sludge layer, carbon dioxide emissions result from anaerobic, facultative, and aerobic reactions. Methane and carbon dioxide were the primary GHGs found in emissions from the septic tank, while carbon dioxide and nitrous oxide were the primary GHGs from the soil dispersal system.

The septic tank methane flux values determined by the flux chamber method were found to be log-normally distributed, with a geometric mean (M_g) of 11.0 g/capita·d and geometric standard deviation (s_g) of 2.50. The geometric mean of the methane flux values from individual septic tanks was found to range from 6.3 ($s_g = 1.40$) to 17.9 ($s_g = 1.94$) g/capita·d, excluding results from one site that had the septic tank pumped recently. A summary of the methane emission rate values found in the literature and measured values using the flux chamber from this study are presented in Table ES-1.

The average rate of methane emission measured with the flux chamber is not in agreement with the IPCC (2007), Winneberger (1984), and Sasse (1998) models. One reason for the difference between the measurements presented here and those determined from the IPCC (2007) model is that the IPCC (2007) model assumes that half of the influent COD to the septic tank is converted anaerobically. Further, the fate of organic matter present in septage and septic tank effluent is not accounted for clearly. It is likely that the measurements made by Winneberger (1984) are high because not enough samples were obtained to establish a statistical distribution. The values used in the Sasse (1998) model were based on statistics from septic tanks located in developing countries, which operate at higher temperatures and loading rates, resulting in higher methane emissions.

Table ES-1. Summary of Methane Emission Rates Including the Flux Chamber Method.

Method	Year	Methane estimate ($g\ CH_4$/capita·d)
Kinnicutt et al.	1910	10.1[a]
Winneberger	1984	14 to 18[a]
COD loading	2009	11[b]
IPCC	2007	25.5[c]
Sasse	1998	18[d]
This study	2009	11.0 ($s_g = 2.50$)[a,e]

[a] Measured value.
[b] Calculated value assuming that 40 % of solids are removed as septage.
[c] Calculated value assuming that half of the influent COD is converted anaerobically.
[d] Calculated value assuming 25 % CH_4 dissolved.
[e] Geometric mean and standard deviation as determined using flux chamber method, this study.

The estimated septic tank emission rates reported in terms of CO_2-equivalent (CO_2e) emissions are summarized in Table ES-2.

Table ES-2. Comparison of GHG Emission Rates as CO_2e from the Septic Tank and Vent Average Measurements.

	Geometric mean emission rate value (g/capita·d)			Carbon dioxide equivalent emissions (tonne CO_2e/capita·year)	
Compound	Septic tank	Septic system[b]	GWP[a]	Septic tank	Septic system[b]
Methane	11.0	10.7	21	0.084	0.082
Nitrous oxide	0.005	0.20	310	0.00057	0.023
Carbon dioxide	33.3	335	1	0.012	0.12
Total GHG emissions				0.096	0.23
Total anthropogenic emissions[c]				0.085	0.10

[a] GWP for a 100 year horizon IPCC (1996).
[b] As determined from vent system sampling.
[c] Biogenic carbon dioxide is not included in GHG inventories (U.S. EPA, 2009).

Major Findings

The principal findings from this research are:

- The geometric mean of the total emission rates for methane, carbon dioxide, and nitrous oxide based on samples from the vent system were 10.7 (s_g = 1.65), 335 (s_g = 2.13), and 0.20 (s_g = 3.62) g/capita·d, respectively.
- The CO_2e of the methane emission rates to the atmosphere, as determined from the vent system data in this study, is about 0.10 tonne/capita·yr. Based on the current estimated per capita CO_2e emission rate for the United States (i.e., 23 tonne CO_2e/capita·yr; U.S. EPA, 2010), the septic tank accounts for about 0.5 percent of the total per capita emission.
- The septic tank methane flux values determined by the flux chamber method were found to be log-normally distributed, with a geometric mean (M_g) of 11.0 g/capita·d and geometric standard deviation (s_g) of 2.50. Similarly, the values of M_g for carbon dioxide and nitrous oxide were 33.3 (s_g = 2.73) and 0.005 (s_g = 4.35) g/capita·d, respectively.

Other Findings

Other findings from this research are:

- There was general agreement for methane gas emission rates determined with theoretical models and measured with the flux chamber and vent methods.
- There is considerable variability in the methane gas fluxes from tank to tank and sample to sample.
- The hardness of the water supply appears to influence the overall flux of carbon dioxide, with soft water systems having higher carbon dioxide gas fluxes.
- A correlation between the GHG emission rates from the septic tank and the liquid temperature was not observed, perhaps as a result of the limited duration of the study.
- The presence or absence of a scum layer had no discernable influence on emission rates of methane and carbon dioxide.
- The carbon (measured as COD) in the septic tank effluent discharged to the soil dispersal system was approximately equal to the amount of carbon being vented (measured as carbon dioxide) from the soil dispersal system.
- Methane generated during the anaerobic digestion process was found in both gaseous and aqueous forms but no relation was found between the gas and liquid phase concentrations.
- Nitrous oxide emission rates from septic tanks were found to be negligible; however nitrous oxide was detected in the gases vented from the soil dispersal system.
- Essentially no gas emissions from the soil surface were measured using flux chambers placed above the soil dispersal system trenches.
- Using the mean methane emission value measured for the septic tanks from this project, an MCF value of 0.22 was calculated.

Recommendations

Based on the findings of this research, the following recommendations are proposed for future studies of greenhouse gas emissions from septic tank systems:

- Due to the uncertainty in several operational parameters, such as temperature and water hardness, and their influence on the production of septic tank gases, further study in other regions of the country is recommended.
- In this study, only direct GHG emissions from operational septic systems were evaluated. A follow up study quantifying the GHG emissions associated with various septage management practices is needed.
- The soil dispersal systems in this study were well drained and did not have any ponding. The evaluation of soil dispersal systems in other soil types and at different stages of ponding is needed. In addition, studies on alternative soil dispersal systems, such as pressure and drip irrigation systems, are needed.
- Only conventional septic tank systems were evaluated in this study. Additional research is needed to quantify gas emissions from alternative onsite wastewater systems, such as natural treatment systems, packed bed filters, and other aerobic treatment processes.
- A study is needed to evaluate the development of methanogenesis in septic tanks from the time of start-up, with and without inoculation.
- The methods for sampling of gases from ventilation systems should be further developed and refined.
- Further study is needed to develop technologies for the control of GHG emissions from wastewater systems is needed, including soil-based filtration and stand-alone biofiltration processes. Integration of these types of control systems may require slight modifications to the aspects of the building code related to septic tank ventilation systems.
- A study is needed to determine the correlation between the GHG emissions and the septic tank influent quality and loading.
- Further work should be conducted to quantify GHG emissions from all types of wastewater management systems so that accurate models can be developed.

CHAPTER 1.0

INTRODUCTION

This study was conducted to determine the emission of greenhouse gases (GHGs) from conventional septic tank systems used for the management of domestic wastewater. The project background, objectives, approach, and report organization are discussed below.

1.1 Background

Concerns with climate change have led to an effort to reduce the emission of GHGs, especially in the state of California, which has enacted regulations related to GHG inventory and mitigation (i.e., AB 32). Methane has been identified as a potent greenhouse gas; equivalent to 25 times that of carbon dioxide. Similarly, nitrous oxide has a reported potency factor of 298 times that of carbon dioxide (IPCC, 2007). Using the IPCC methodology, the U.S. EPA (2009) has determined that a majority of the methane emissions associated with wastewater originate from conventional septic tank systems, due to the large number of individual septic systems now in use. However, the actual data currently available on the emission of methane from septic systems are insufficient to produce an accurate GHG inventory for these systems.

In the IPCC (2007) method used currently to compute GHG emissions from septic tank system it is assumed that half of the influent organic matter is converted to methane. Using the IPCC model, the carbon dioxide equivalent (CO_2e) of the methane released from individual domestic septic tanks is about 0.24 tonne CO_2e/capita·yr. However, based on historical studies of methane emissions from septic tank systems, the value is estimated to range from about 0.09 to 0.16 tonne CO_2e/capita·yr. In addition, these estimates only consider emissions from the septic tank and do not account for emissions from the soil dispersal systems. Thus, there is a need to develop a more detailed model of the production of GHGs from septic tank systems.

1.2 Objectives

The principal objective of the research was to obtain more accurate data on GHG emissions from septic tank systems, focusing on methane emissions from conventional septic systems. To achieve the proposed objective the following activities were performed:

- Extensive literature review on septic tanks and gas formation pathways.
- Construction of flux chambers and development of a method for gas sampling from septic tanks.
- Development of sampling techniques and a protocol for gas sampling from septic system drainage and ventilation piping.
- Identification and selection of appropriate field sites for collection of study data.

- Collection of gas samples from the septic tank liquid surface, vent system, and soil dispersal system over a six-month period.
- Analysis of results and determination of estimated GHG emission rate values.

1.3 Project Approach

Methods for the measurement of GHG emissions from soil-plant ecosystems using flux chambers are well established; however, little information is available on gas flux measurements from the liquid/solid surface of septic tanks. Hence, for this research a flux chamber design, based on the design used for soil-based measurements, was constructed and tested, along with the development of a corresponding sampling methodology. The flux chamber method was also used for gas sampling of the soil dispersal system. In addition, a sampling device and methodology were developed to measure the mass flow of GHGs through the vent system. Methane, carbon dioxide, and nitrous oxide emission rates were measured in this study.

1.4 Report Organization

This report is organized into seven chapters. The first chapter provides an introduction and purpose for this project. A detailed literature review on septic tank systems, characteristics, processes, and GHG emissions is presented in Chapter 2.0. The methods employed during and in support of field monitoring are described in Chapter 3.0. A description of the field sites is presented in Chapter 4.0. The results of the gas flux measurements in the septic tank, venting system and soil dispersal system, a mass balance analysis, and the sources of variability in the gas emission rates are discussed in Chapter 5.0. The implications of the results from the research study are presented in Chapter 6.0. Findings and recommendations for further study are summarized in Chapter 7.0. Calculations and support materials are presented in the appendixes.

CHAPTER 2.0

LITERATURE REVIEW

To assess the potential for the release of greenhouse gases from septic tanks, the characteristics of onsite systems are reviewed in this chapter. The subjects considered in this review include an overview of the development of septic tank systems, the physical characteristics and operation of septic tanks, the fundamentals of the anaerobic processes occurring in septic tanks, and the information that exists on the emissions from septic tanks and other wastewater sources.

2.1 Overview of Septic Tank Systems

The septic tank is one of the oldest units available for the primary treatment of wastewater from decentralized sources. The historical background of the septic tank and its importance in decentralized wastewater treatment systems are discussed in this section. An introductory overview of gaseous emissions from septic tanks is also presented along with a brief description of venting systems and the soil absorption field.

2.1.1 Historical Background

Wastewater from individual buildings and small communities is often managed using onsite wastewater systems when a centralized wastewater collection system is not available. Nearly all onsite wastewater systems incorporate a septic tank for primary treatment of influent wastewater (Crites and Tchobanoglous, 1998). A septic tank is a buried, watertight tank designed and constructed to receive and partially treat raw wastewater (U.S. PHS, 1957; U.S. EPA, 2009). It is estimated that about 25 million septic tanks are currently in use in the United States (U.S. EPA, 2002).

Septic tanks were first reported as wastewater treatment systems in the 1860s in France. The Fosse Mouras automatic scavenger was patented in 1881, based on the work of Abbe Moigno and Louis M. Mouras (Dunbar, 1908; Winneberger, 1984). An illustration of the Fosse Mouras septic treatment process is presented on Figure 2-1. The process configuration since that time remains almost unchanged when compared to modern septic systems (Crites and Tchobanoglous, 1998).

2.1.2 Onsite Wastewater Treatment Systems

The key functions of the septic tank are to separate and retain settleable solids (sludge) and floatables (scum) from the incoming wastewater. Subsequently, the treated wastewater is discharged typically into a soil dispersal system, also known as a leach field. The captured solids are retained in the septic tank and undergo a passive (naturally occurring and uncontrolled) anaerobic digestion (Tchobanoglous and Schroeder, 1985). The combination of septic tank and leach field, shown on Figure 2-2, is the most commonly used onsite wastewater treatment system. Other types of primary treatment processes used in decentralized wastewater systems include Imhoff tanks, anaerobic baffled reactors, and upflow anaerobic sludge blanket reactors (Crites and Tchobanoglous, 1998; U.S. EPA, 1999). However, these alternative primary treatment processes are not used commonly due to their more complex construction and operation. As shown on Figure 2-2, the septic tank is connected to a building through subsurface drainage pipes and the treated wastewater (septic tank effluent) is discharged to the soil dispersal system (U.S. EPA, 2000).

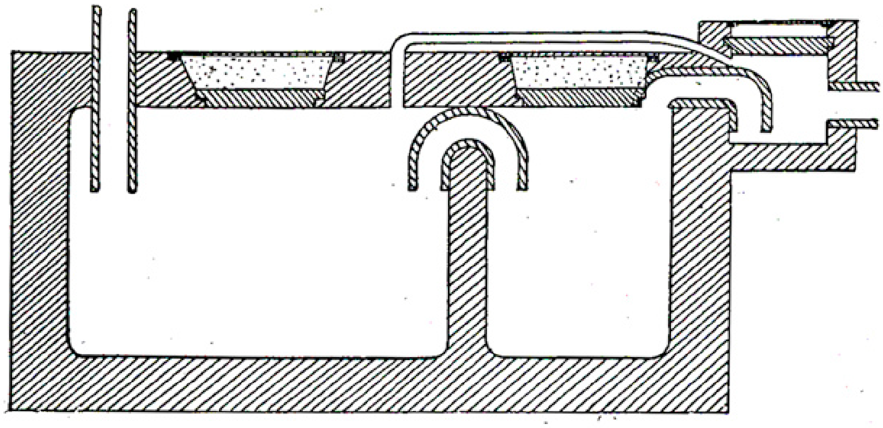


Figure 2-1. Illustration of the Mouras Automatic Scavenger. Adapted from Dunbar, 1908.

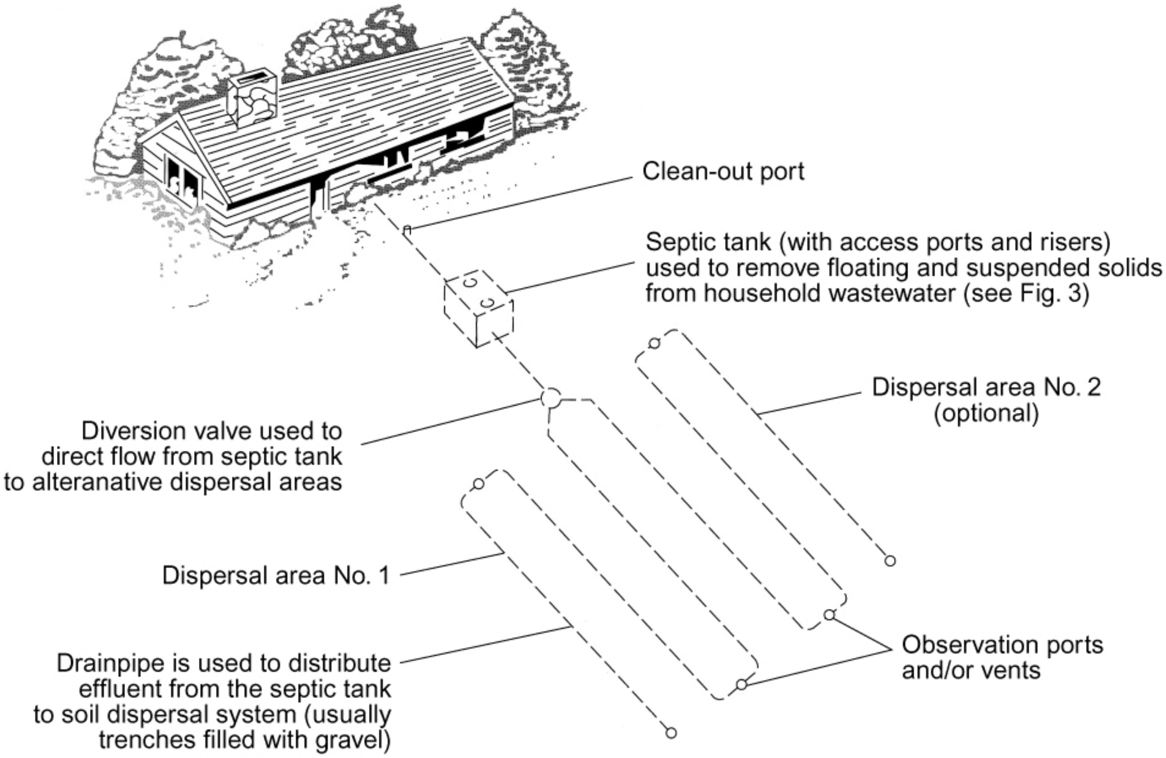


Figure 2-2. Onsite Wastewater Treatment System Consisting of a Septic Tank and Soil Dispersal System. Adapted From Tchobanoglous, G. and F.L. Burton, 1991**.**

2.1.3 Gas Emissions from Septic Tanks

Anaerobic degradation, occurring within the sludge layer of the septic tank, results in the production of gases composed primarily of methane and carbon dioxide. When sulfate compounds are present in the influent wastewater, hydrogen sulfide and other sulfur containing gases may also be formed. Gases formed in the septic tank are evacuated typically from the system through the building drainage plumbing and vent system. Gas emissions are discussed in more detail in Section 2.4.

2.1.4 Venting Systems

Building codes require that gases formed inside the septic tank be evacuated by means of a vent system. Household plumbing vents are used generally as vents for the septic tanks. Less commonly, gases may also be vented through the leach field or through screened atmospheric pipes located inside the tank (D'Amato et al., 2008). The two main purposes of tank vents are to avoid wastewater backflow due to a vacuum created inside the house plumbing fixtures and to let toxic, odorous (e.g., hydrogen sulfide, mercaptans), and explosive (e.g., methane) gases formed during the anaerobic degradation escape and be diluted in the atmosphere (Kaplan, 1991).

Gases such as hydrogen sulfide often generate concern due to odor generation, potential human toxicity, and ignition properties (D'Amato et al., 2008; EPA-IRIS, 2009). Nevertheless, based on measurements reported by Winneberger (1984), the hydrogen sulfide concentration from vented tanks are below detection limits and, therefore, gas evacuation throughout venting systems does not represent a fire risk for the household residents. It has been shown that gases in the headspace of the tank escape through the inlet and outlet tees and eventually to the house vents (Winneberger, 1984).

2.1.5 Effluent Dispersal

In a conventional septic system, clarified effluent is discharged typically to a soil dispersal system (see Figure 2-2). The soil dispersal system receives the treated wastewater and distributes it into the soil through a perforated pipe system located in gravel filled excavated trenches (U.S. EPA, 2003). The soil operates as a biofilter, where biological, physical, and chemical processes take place. Inorganic and organic compounds may be transformed to various degrees in the soil while pathogens die off.

Operationally, problems can occur in the soil dispersal system when the application of septic tank effluent exceeds the infiltration capacity of the soil. The infiltration capacity of the soil is a function of the soil properties and characteristics of the septic tank effluent. In general, loading of dissolved organic matter supports the growth of biomass that restricts soil pore space, while the loading of particulate matter fills and blocks soil pores (Leverenz et al., 2009). Thus, a high loading of both dissolved and particulate organic matter will result in a reduced infiltration rate. In the extreme case, effluent can surface above the soil dispersal field, which is an indication that the hydraulic loading rate has exceeded the soil infiltration rate for the given loading scenario (Crites and Tchobanoglous, 1998). Proper septic tank design, along with regular monitoring and maintenance, can be used to control the discharge of constituents that will reduce the infiltration capacity. The discharge of chemical and biological constituents to groundwater is also a concern associated with onsite wastewater systems.

2.2 Septic Tank Characteristics

Septic tanks are considered simple and effective primary treatment systems; however, there are several important processes that must occur to achieve a satisfactory level of treatment. General system configurations, hydraulics, processes occurring within septic tanks, impacts of invertebrate animals, and a description of the tank operation and maintenance, with a focus on sludge accumulation and solids extraction frequency, are described in this section.

2.2.1 Process Configuration

The general configuration of a septic tank is shown on Figure. 2-3. The tank liquid capacity varies between 2.8 and 5.6 m^3 (750 and 1500 gal) when used for a single house (Tchobanoglous and Schroeder, 1985), with specific tank sizing based on parameters such as the number of inhabitants, the home maximum occupant capacity, and use of water-saving fixtures (U.S. EPA, 2000). Septic tanks are constructed typically of concrete or fiberglass, but can also be made of polyethylene (Crites and Tchobanoglous, 1998; U.S. EPA, 2000).

As shown on Figure 2-3, most modern septic tanks have access ports or risers at grade for inspection and cleaning activities. Riser lids should be secured or locked to prevent unauthorized access. Septic tanks are generally buried in the ground and must be watertight and structurally sound to prevent leakage and eventual failure (U.S. EPA, 2000). Other components are the inlet tee, effluent filter (optional), and outlet tee, which are designed to retain solids in the tank while allowing the clarified water and gases to move through the tank. Ribbed risers are sometimes not recommended in cold climates where the soil freezing can uplift and displace the risers from the septic tank.

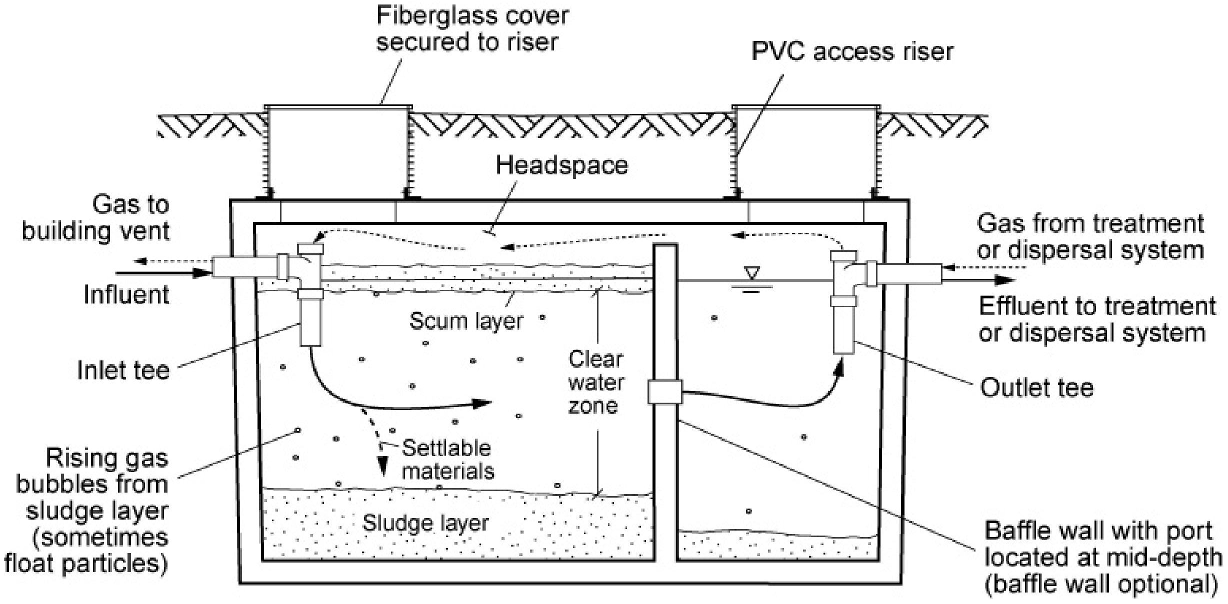


Figure 2-3. Sectional View of Dual Compartment Septic Tank.
Adapted from Crites and Tchobanoglous, 1998.

2.2.2 Tank Hydraulics

A septic tank can have one or two compartments (Crites and Tchobanoglous, 1998). The two-compartment tank is recommended by the uniform plumbing code (UPC) to aid in the retention of solids (Perkins, 1989; D'Amato et al., 2008); however, Winneberger (1984) found that a single compartment tank performed as well, with respect to effluent quality, as a two-compartment model with the same capacity. One explanation is that a single compartment tank has a larger surface area available, and therefore the settling may be more efficient (Crites and Tchobanoglous, 1998). In general, the results of the septic tank compartment findings have been ambiguous due to the lack of long term studies (Bounds, 1997). Different baffle configurations can be used to improve tank hydraulics and facilitate sludge removal.

In general, the tees control the flow of liquids and solids in the tank and act as a pathway for gases to leave the tank into the house vent system. Tees also help to avoid short-circuiting of the wastewater through the tank to the outlet and prevent mixing between the scum and the incoming liquid (Bounds, 1997; U.S. EPA, 2002). The invert elevation of the outlet tee is generally located 2 to 3 inch below the invert elevation of the inlet tee to keep the inlet pipe above the water level. The rising leg of the inlet tee should extend up in length at least 6 inch over the liquid level to prevent the scum layer from clogging the inlet (U.S. EPA, 2000).

The inlet tee (see Figure 2-3) allows the incoming wastewater to be introduced without disturbing the clarification process that is taking place inside the tank (Winneberger, 1984; Perkins, 1989). Further, the tee minimizes short-circuiting (U.S. EPA, 2002) and enhances sedimentation and detention time (Bounds, 1997). The outlet tee prevents scum and floating sludge from passing through and clogging the soil dispersal system (Winneberger 1984; Perkins, 1989).

The hydraulic retention time (HRT) in a septic tank is directly related to the tank geometry. Of tanks with similar volumes, shallow tanks with greater surface area have lower overflow rates and as a result more efficient capture of solids, while deep tanks can store more settled solids (U.S. EPA, 2000; D’Amato et al., 2008). The typical theoretical HRT for septic tanks varies from 24 to 72 hr (D’Amato et al., 2008); higher values of HRT ranging from 60 to 80 hr have also been reported (Walker and Driftmier, 1929). Other studies recommend values ranging from 6 to 24 hr (Winneberger, 1984; Bounds, 1997). A summary of HRT recommendations is presented in Table 2-1.

Table 2-1. Recommended Hydraulic Retention Time in Septic Tanks.

Range (hr)	Reference
6 – 24	Winneberger (1984) Bounds (1994)
24 – 72	D’Amato et al. (2008)
60 – 72	Walker and Driftmier (1929)

The actual HRT depends on the geometry, depth, number of compartments, solids volume, and inlet and outlet designs of the septic tank and thus varies greatly from tank to tank (U.S. EPA, 2002). When hydraulic overloading occurs, the usual retention time of the septic tank might not be long enough to allow for effective settling, resulting in solids flow through the tank outlet and obstruction of the effluent dispersal system or downstream process.

2.2.3 General Conversion Processes Occurring in Septic Tanks

In a simplistic view, the septic tank operates as a settling basin allowing the influent wastewater particles to settle to the bottom and form a solids layer known as sludge (U.S. EPA, 2003). Greases, oils, and other buoyant particles rise to the water surface and form a scum layer composed of accumulated floating materials (Crites and Tchobanoglous, 1998; U.S. EPA, 2005). As depicted on Figure 2-3, a septic tank would generally have three characteristic layers: scum at the top, a clear zone in the middle, and the sludge layer at the bottom. The clarified water flows between the scum and sludge layers and leaves the septic tank for further treatment (if present) or soil dispersal.

The major mechanism of oxygen demand (OD) removal from septic tank effluent results from the settling of suspended solids from the influent wastewater to the bottom of the tank. While the liquid remains in the tank one or two days (see Table 2-1), the settled solids remain in the tank and undergo anaerobic decomposition over a long period of time, for example 5 to 15 yr (Rittman and McCarty, 2001). The biochemical oxygen demand (BOD) of the septic tank effluent is typically 25-50% less than the BOD of the influent (Crites and Tchobanoglous, 1998; U.S. EPA, 2005).

The proper operation of a septic tank is based, in part, on the development of a facultative and anaerobic environment in which microorganisms perform complex biochemical reactions. The bottom portion of the septic tank behaves, for the most part, as an anaerobic reactor; however, at or near the water surface, the presence of oxygen results in facultative as well as aerobic reactions (D'Amato et al., 2008). Wastewater characteristics such as temperature, organic loading, hydraulic loading, detergents, chemicals, and cleaning products can encourage or inhibit microbial development (Bounds, 1997). For example, it has been reported that gas production and digestion activity in sludge is temporarily inhibited by discharge of water softener brine to septic tanks (Seabloom et al., 2005).

Organic material entering the sludge layer of the septic tank undergoes hydrolysis, where bacteria partially transform complex organic molecules into simple molecules, a process also known as liquefaction (Crites and Tchobanoglous, 1998; D'Amato et al., 2008). Simple organic molecules are then converted to short chain length volatile fatty acids (VFAs) by acid-forming bacteria in a process known as acidogenesis, resulting in a decrease in the water pH. At this point, methanogens begin to convert the VFAs into carbon dioxide and methane in a process called methanogenesis (Crites and Tchobanoglous, 1998; D'Amato et al., 2008). A more detailed description of the methanogenesis process is presented in Section 2.3.

Methanogenesis occurs spontaneously in septic tanks, but the conditions that determine the start of anaerobic digestion have not been elucidated fully. It has been reported that, based on observations of gas production, the methanogenesis activity inside community septic tanks is readily established (Kinnicutt et al., 1910) perhaps due to the high organic loading rate (OLR), but may not reach a peak until two years of operation in a septic tank for an individual home (Philip et al., 1993), which are usually operated at a lower OLR. Weibel et al. (1949) determined that the use of a seed inoculum (anaerobic sludge from an Imhoff tank) added at startup at a rate of about 23 L/capita·d resulted in the rapid development of anaerobic digestion. It should be noted that tank seeding is not practiced commonly.

In studies on septic tanks carried out by Weibel et al. (1955), it was reported that for a small capacity tank started in the winter, a five month lag phase was observed. The lag phase was characterized by low pH and offensive odors, which are associated with hydrolysis and acidification. Methanogenesis began to occur gradually as the temperature increased during summer. The onset of methanogenesis was characterized by increased pH, reduced effluent volatile suspended solids, and a reduction in odor. For the same tank, cleaned out and restarted in the spring, there was a shorter lag phase, which was not accompanied by low pH or offensive odors. Weibel et al. (1955) suggested that the effects of process startup may be less extreme in larger tanks and that a seed inoculum be considered for starting tanks in the winter to avoid odor generation.

Methane can also be consumed by methanotrophic bacteria under aerobic conditions, converting the methane to carbon dioxide. Methane consumption has been observed in some anaerobic/aerobic environments, but has not been measured in septic tank systems. It is reasonable to assume that methanotrophic activity could exist in septic tanks at the air-water or air-scum interface where oxygen and methane are present together (Knowles, 1993).

2.2.4 Invertebrate Communities in Septic Tanks

Invertebrate communities are commonly found within septic tanks; however the role of the individual species on degradation processes occurring in the tank is not clear. Dunbar (1907) observed that thick scum layers were composed of condensed plant remains, paper, hair, and other residual matter. According to Dunbar, this condensed material was transformed by fungi action (e.g., *Peziza omphalodes*) into a mass, where a variety of invertebrates such as worms, earthworms, and larvae of some insects (in particular, Psychoda phaloenoides) were encountered. Nevertheless, a clear relation between the action of invertebrate animals and the scum thickness was not entirely demonstrated.

In a study carried out at Novato, California, it was found that Diptera, Collembola, Acarina, Nematoda, Isopoda, and Oligochaeta are the dominant species living within the septic tanks (Dale, 1982). Dale reported that the thickness of the scum layer was directly related to the number of organisms present. A larger number of organisms corresponded to a thicker layer of scum.

The visual characteristics of the scum depend, in part, on the type of invertebrate animal species present. For example, Dale observed that scum layers had a humus look when *Lumbricidae* were present. Winneberger (1984) also reported that the scum upper layers were usually dark brown to black and had the appearance of “crumbly earth” or humus, and were frequently populated by earthworms. Thus, it appears that the configuration of the scum layers involves more than buoyant solids rising to the liquid surface; some invertebrate animals may also participate in its development, degradation, and thickness.

2.2.5 Operation and Maintenance

As stated previously, incoming solids accumulate in the tank forming a sludge and scum layer. Sludge and scum accumulation depend on several factors including tank design, the use of garbage grinders, user diet, season of the year, and temperature. These factors and their influence on the sludge accumulation are summarized in Table 2-2. Both scum and sludge layers will increase in thickness with daily solids additions and eventually the removal of all of the accumulated solids from the tank is necessary to avoid malfunctioning of the system.

Based on a number of studies, it has been found that the sludge and scum accumulation rates are highly influenced by the temperature and season of the year. Walker and Driftmier (1929) reported that the thickest scum measurements were obtained during early summer when increasing temperatures were recorded. Walker and Driftmier (1929) also reported an increase in sludge accumulation during the winter months, when bacterial degradation is hindered by the lower temperatures. These observations also support the concept of the 'spring boil', where high rates of gas bubble release are observed (see also Section 2.4.1). During the winter months, when the temperature in the septic tank cools, the rate of digestion slows and solids begin to accumulate, increasing the thickness of the sludge layer. Microbial activity in the sludge layer increases when the tank contents warm during the spring and early summer, resulting in an increase in gas production. Also, the solubility of dissolved gases decreases as the contents of the tank become warmer, also increasing the release of gases. The gas bubbles may rise to the surface individually, but also float solids to the surface. The buoyant solids then become part of the scum layer, thus increasing the thickness of the scum layer, or are discharged with the effluent.

Table 2-2. Summary of Factors Affecting the Accumulation of Sludge and Scum in Septic Tanks.

Factor	Summary	Reference
Food waste grinder	A total increase of 77% (210% increase in scum and 31 % increase in sludge) in the amount of sludge and scum from households using food waste grinders.	Weibel et al. (1955)
	The use of food waste grinders enhanced the buildup of scum by 34%, while sludge accumulation increased by 2%.	Bounds (1997)
	Homes with food waste grinders had an increase of total suspended solids in the septic tank of 25 - 40 % compared to houses without them.	U.S. EPA (2002)
	Houses with food waste grinders have been reported to accumulate sludge and scum at a higher rate.	D'Amato et al. (2008)
House occupant diet	It was observed during routine inspections that tanks from household occupants with preferences for vegetarian diets developed thin or no scum layers.	Ball (2009)
	It was observed that the tank for a vegetarian family did not develop a scum layer compared to households with a conventional meat-based diet.	Winneberger (1984)
Season and temperature	Scum thickness increased during highest recorded temperatures of the year (early summer). During winter, when bacterial activity decreased, a thick layer of sludge was noticed.	Walker and Driftmier (1929)
	In cold months (winter season) solids built up rapidly in the bottom of the tank.	Winneberger (1984)
	Solids accumulation rate increased during the winter months.	D'Amato et al. (2008)

Solids accumulation rates are also related to the maintenance of the septic system. Based on these rates, the cleaning frequency of the tank can be determined. Other factors that influence the solids accumulation and pumping frequency are the size of the tank, specific design, number of people in the home, water usage, and household water fixtures (Weibel et al., 1955; Bounds, 1997; U.S. EPA, 2002; D'Amato et al., 2008).

Data on the average rates of sludge and scum accumulation in septic tanks from various studies are summarized on Figure 2-4 (Bounds, 1997; Crites and Tchobanoglous, 1998). The different sludge accumulation values in septic tanks reported in the literature are shown on Figure. 2-4.

Reported sludge pumping intervals differ from study to study, and sometimes are not even reported (U.S. EPA, 2002). Other pumping intervals recommended are based on the percentage of solids accumulation inside the tank. A summary of sludge extraction periods recommended in various studies is presented in Table 2-3.

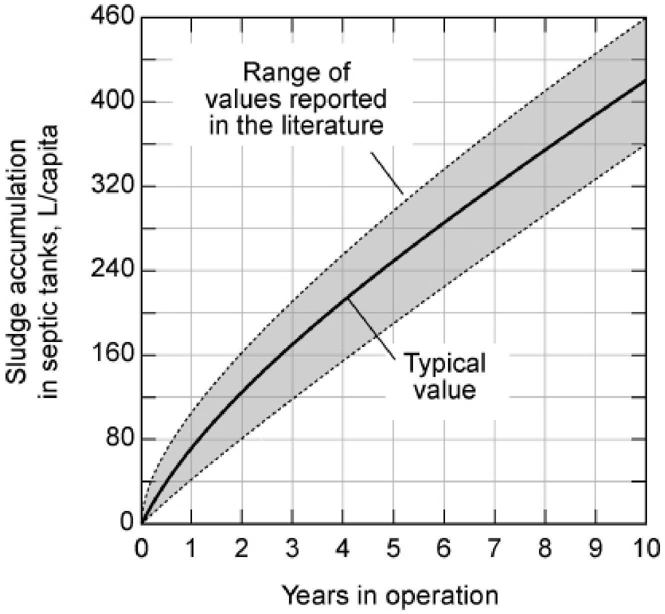


Figure 2-4. Sludge and Scum Accumulation Rates from Different Studies.
Adapted from Crites and Tchobanoglous, 1998.

As reported in Table 2-3, there is little agreement on the appropriate sludge withdrawal frequency; thus, the reported intervals can only be considered to be a guideline for pumping protocols. In some studies, equations have been given that can be used to predict the septage (i.e., entire tank contents) pump intervals based on different variables such as loading, tank size, house occupants, and use of a garbage disposal (Weibel et al., 1955; Bounds, 1997). However, regular inspection and an improved understanding of the bacterial activity in the different layers of the tank and the carbon degradation pathways are needed.

Although septic tanks are presumed to require little maintenance, periodic inspection of the scum and sludge layers, watertightness, and structural soundness are recommended to avoid environmental damage and/or health risks (Crites and Tchobanoglous, 1998; U.S. EPA, 2002). Operation and inspection guidelines have been published for septic tank owners to encourage routine inspections to protect the system from failure (U.S. EPA, 2005).

Table 2-3. Summary of Septic Tank Pumping Guidelines Reported in the Literature.

Guideline reported	Reference
Scum layer within 3 inch of the outlet elevation or the sludge layer within 6 inch of the outlet elevation	U.S. PHS (1957)
Sludge plus scum greater than ½ to ⅔ of tank depth	U.S. EPA (2002)
Sludge plus scum equal to ⅓ of tank volume	U.S. EPA (2002)
Sludge plus scum equal ¼ of the tank volume	GDPUD (2009)[c]
Every 2 years	U.S. EPA (2002)
Every 3 to 5 years[a]	U.S. EPA (2002)[b]
Every 5 years or more	Phillip et al. (1993)
Every 10 years	SLOC (2008)
Floating sludge and scum flowing through the outlet tee	U.S. EPA (2002)

[a] Range applied when regular inspections have not been done during those years.

[b] U.S. EPA recommends monitoring of the sludge and scum layers every two years and then using the natural accumulation rate for that area or that tank as the guide to determination of pumping frequency.

[c] Specific example of regulatory standards applied to the community based on site characteristics.

2.3 Anaerobic Processes

Because sludge accumulating in the bottom of a septic tank undergoes anaerobic decomposition, it is important to review the fundamental principles underlying anaerobic processes to develop a more comprehensive view of the chemical and biological reactions occurring inside a septic tank. The essential reactions that occur during anaerobic decomposition, the key operational parameters, and toxic conditions that affect the process are presented and discussed in this section

2.3.1 Anaerobic Oxidation

The anaerobic oxidation process can be described as a two-stage process (see Figure 2-5); the first stage is identified as *waste conversion (acetogenesis, acidogenesis)*, in which complex organics are first hydrolyzed and then fermented into simple organic compounds (e.g., hydrogen and carbon dioxide) and VFAs (e.g., acetate) by facultative bacteria known as acetogens and acidogens (McCarty, 1964; Speece, 1996; Bitton 2005). After the organic matter has been converted to simpler compounds, *waste stabilization (methanogenesis)* takes place, where the acids are synthesized by methanogens into methane and carbon dioxide (McCarty, 1964). It should be noted that in some references anaerobic oxidation is considered to be a three-stage process in which the hydrolysis of the organic material to simple acids is considered to be a separate step (see Figure 2-6).

A key factor in the anaerobic oxidation process is the balance between the microorganisms responsible for each step. When the system is in equilibrium, the methanogens transform the acids at the same rate that acids are formed (McCarty, 1964). Therefore, when high acid concentrations are found, it is an indication that the acid forming bacteria and the methanogens are not in balance.

The two major mechanisms of methane formation are the breakdown of acetic acid, which is the most prevalent volatile acid produced in the fermentation of carbohydrates, proteins, and fats, and the reduction of carbon dioxide (McCarty, 1964; Bitton, 2005). The chemical reactions of methane formation are as follow:

1. Utilization of acetic acid:

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad \text{(Eq. 2-1)}$$

2. Reduction of carbon dioxide:

$$CO_2 + 8H \rightarrow CH_4 + 2H_2O \qquad \text{(Eq. 2-2)}$$

Growth and acid utilization rates of methane formers are slow, and are usually limiting factors in anaerobic treatment (Speece, 1996, Duncan and Horan, 2003). Methanogens are known to be different from the typical bacteria and are classified in a separate kingdom, the Archaea (Duncan and Horan, 2003). The methane forming microorganisms are strict anaerobes and even small amounts of oxygen can be toxic. Methanogens are also sensitive to any environmental change including temperature, organic loading, waste composition, and other factors (McCarty, 1964). The microorganisms involved in the anaerobic process need sufficient concentrations of nutrients to operate properly. Nitrogen and phosphorus comprise about 11% and 2% of the dry weight of biological solids, respectively (McCarty, 1964).

The methanogenic organisms are restricted in the number of reactions and substrates they can utilize. Moreover, according to their substrate specificity, methanogens are classified in two groups, 1) the *Acetoclastic Metanogens*, which in general are able to utilize acetate (e.g., *Methanosaeta* spp. and *Methanosarchina* spp.) and in some cases are capable of using

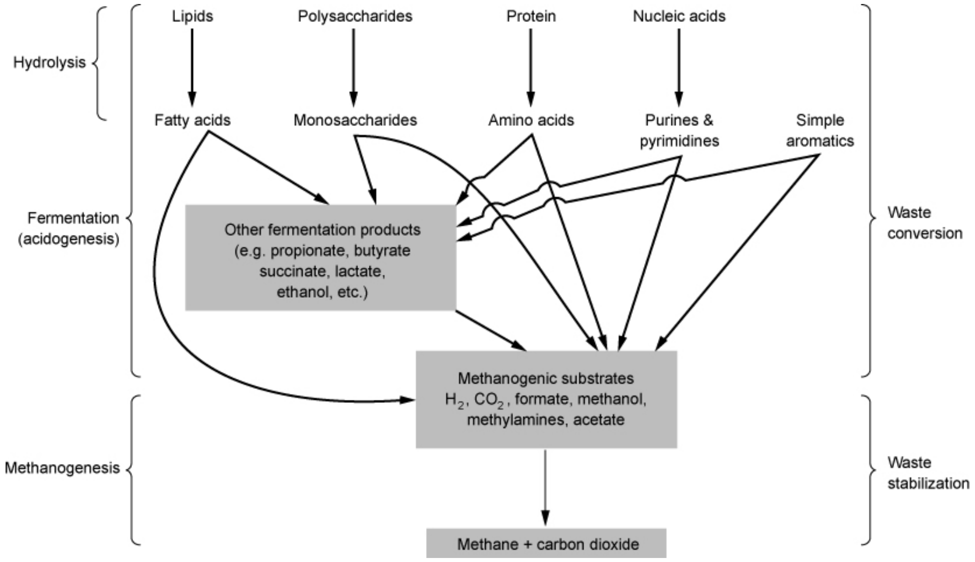


Figure 2-5. The Stages of Anaerobic Decomposition, Waste Conversion Followed by Waste Stabilization.
Adapted from McCarty, 1964 and Tchobanoglous et al., 2003.

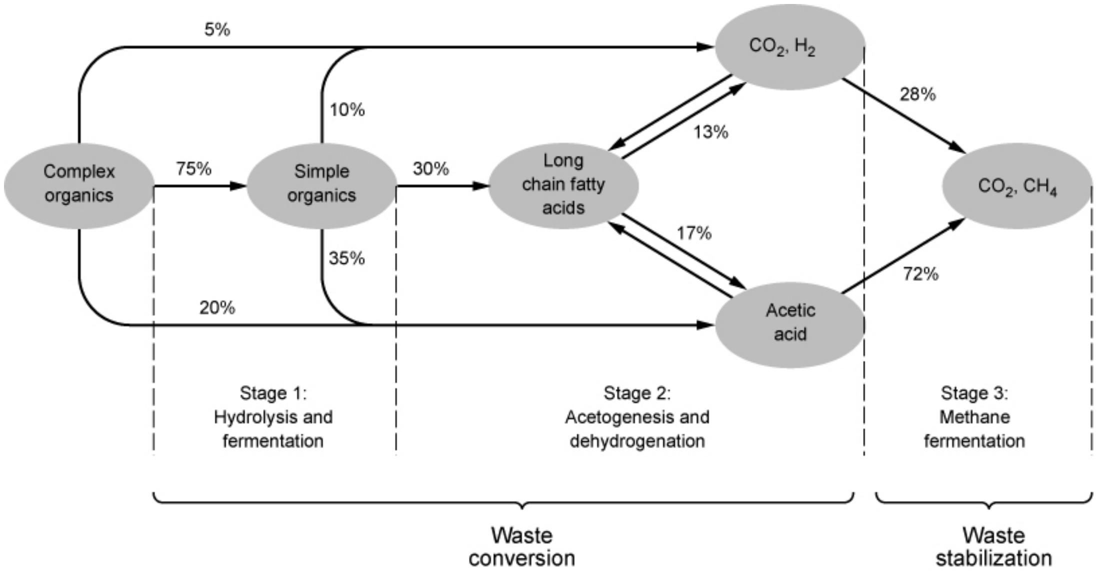


Figure 2-6. The Intermediate Steps of Anaerobic Reactions, with Percentages Based on COD Conversion.
Adapted from Speece, 1996 and Tchobanoglous et al., 2003.

methanol and methylamines (e.g., *Methanosarcina* spp.), and 2) the *hydrogen-utilizing methanogens* that reduce carbon dioxide, formate, methanol, and methylamines, using the hydrogen produced previously during the hydrolysis and acid formation processes (Duncan and Horan, 2003). In anaerobic digesters, 70% of the methane gas is originated from acetate reduction and 30% is attributed to the substrates reduced by the hydrogen-utilizing methanogens (Duncan and Horan, 2003).

A COD balance can be used to estimate the theoretical methane production during anaerobic fermentation. The COD of the methane produced during anaerobic decomposition of organic matter is approximately equal to the COD of the converted organic matter (Tchobanoglous et al., 2003). The oxygen demand of methane is determined as follows (McCarty, 1964):

$$CH_4 + 2O_2 \rightarrow CO_2 + H_2O \qquad \text{(Eq. 2-3)}$$

From Eq. 2-3, it can be derived that each mol of methane is oxidized with two mol of oxygen. Therefore, 0.35 L of methane is equal to one g COD stabilized (5.62 ft^3 CH_4 / lb COD) (McCarty, 1964; Speece, 1996; Tchobanoglous et al., 2003).

2.3.2 Operational Parameters in Anaerobic Reactors

Parameters such as the appropriate concentration of nutrients, pH, redox potential, alkalinity, volatile suspended solids loading, temperature, and solids retention time are important for successful anaerobic digestion.

In anaerobic reactors, the recommended nutrient loading is 5 to 15 mg N/g COD and 0.8 to 2.5 mg P/g COD. Nutrients must be supplied in this range as a preventive measure to avoid inhibiting effects (Speece, 1996). Sulfur is also required by methanogens, but in relatively lower concentrations, for optimal growth and maximum methanogenesis activity (Speece, 1996; Tchobanoglous et al., 2003). For comparison, typical nitrogen and phosphorus concentrations in untreated wastewater from individual residences are 13.3 and 3.28 g/capita·d, respectively

(Crites and Tchobanoglus, 1998). Based on typical operation, the estimated loading of nitrogen and phosphorus in the septic tank sludge is approximately 11 and 6.2 mg/g COD, respectively (see Table 2-6).

The pH is another important factor, which should be in the range of 6.5 to 8.2, with an optimum range of about 7.0 to 7.2 (McCarty, 1964; Speece, 1996). Outside of these ranges, the efficiency of the treatment decreases rapidly, and acid conditions can dominate the reactor environment resulting in toxic conditions for methanogens (McCarty, 1964). Therefore, controlling the reactor pH at the optimum levels is essential for efficient methanogenesis.

Microbial respiration requires an electron acceptor, which can be an organic compound or some inorganic electron acceptors, as shown in Table 2-5. Some of the most common electron acceptors in decreasing order of reduction potential are nitrate, manganese, iron, sulfate (all under anoxic conditions) and finally carbon dioxide, under anaerobic conditions (Maier et al., 2009). As reported in Table 2-5, aerobic reactions using oxygen as a terminal electron acceptor provides the most energy for cell growth, while methanogenesis provides the least. Thus, on the basis of energetics, other electron acceptors must be exhausted before methanogenesis can take place. Based on the relationships shown in Table 2-5, measurements of redox potential can be used to assess the types of reactions likely to be occurring within a septic tank.

Table 2-4. Optimum Conditions for Anaerobic Treatment.

Adapted from McCarty, 1964.

Parameter	Unit	Optimum condition
Temperature	°C	30 - 38[a] 50 - 57[b]
Environment	-	Anaerobic
Biological nutrients available	-	Nitrogen, phosphorous, and sulfur
pH	unitless	7.0 to 7.2
Toxic materials	-	Total absence
Alkalinity	mg/L as $CaCO_3$	2,500 to 5,000

[a] Mesophilic conditions.

[b] Thermophilic conditions.

Table 2-5. Common Electron Acceptors, Products, and Redox Potentials.

Adapted from Maier et al., 2009.

Type of respiration	Reduction reaction electron acceptor→product	Reduction potential (V)	Difference [a,b] (V)
Aerobic	$O_2 – H_2O$	+ 0.81	- 1.28
Denitrification	NO^{3-} - N_2	+ 0.75	- 1.22
Manganese reduction	Mn^{4+} - Mn^{2+}	+ 0.55	- 1.02
Nitrate reduction	NO^{3-} - NH_4^+	+ 0.36	- 0.83
Sulfate reduction	SO_4^{2-} - HS^-, H_2S	- 0.22	- 0.25
Methanogenesis	$CO_2 – CH_4$	- 0.25	- 0.22

[a] CH_2O-CO_2 was used as electron donor in each case, with an oxidation potential equal to – 0.47 V.

[b] Reduction - oxidation potential of CH_2-CO_2.

In anaerobic reactors, the alkalinity is controlled by the bicarbonate ion concentration, associated with the production of carbon dioxide gas. Optimum levels of alkalinity in a complete-mix high-rate anaerobic digester vary from 2,500 to 5,000 mg/L as $CaCO_3$, with a minimum of 1,000 mg/L as $CaCO_3$ to provide enough buffer capacity (McCarty, 1964). When the levels of alkalinity are less than 1,000 mg/L as $CaCO_3$, the pH will drop and the methanogenesis rate will be reduced (McCarty, 1964; Speece, 1996).

Similar to anaerobic digesters, the anaerobic sludge layer in the septic tank requires enough alkalinity to buffer against pH change due to the production of volatile fatty acids (VFAs). However, the formation of VFAs depends directly on the incoming organic loading rate (OLR), with a higher OLR resulting in a higher concentration of VFAs in the septic tank. The OLR in anaerobic reactors is usually high (3.2 to 32 kg COD/m^3·d) as compared to 0.07 kg COD/m^3·d in septic tanks (see Appendix A for calculation). While high alkalinity concentrations (e.g., 2,500 to 5,000 mg/L as $CaCO_3$) are not required to buffer acidic conditions inside the septic tank, the estimated alkalinity in the septic tank sludge layer is on the order of 5,000 mg/L (calculated using septage values from U.S. EPA, 1994).

Temperature is also a relevant parameter affecting the rate of anaerobic digestion. Thermophilic temperatures are ideal in anaerobic reactors because the reaction rates increase and the process is more efficient (McCarty, 1964). Temperature also affects ionization fractions, the solubility of substrates, and iron bioavailability (Speece, 1996). In the anaerobic consortium, methanogens are more sensitive to small changes in temperature compared to acid-forming bacteria. As temperature reduces, acidogens produce VFAs faster than methanogens can convert the VFAs to methane, creating an unbalanced metabolism during the anaerobic process (Speece, 1996; Bitton, 2005). The two temperature ranges specified for anaerobic treatments are reported in Table 2-4. Nevertheless, keeping the temperature at thermophilic ranges can be challenging, especially when the incoming waste is diluted, because the methane production might not be sufficient to heat the process using gas combustion (McCarty, 1964; Speece, 1996). In anaerobic digesters, a supplemental external heat source is often used. The liquid temperature in a septic tank is basically uncontrolled and related to hot and cold water use, as well as mean annual temperature. It should be noted that low temperatures in septic tanks are compensated by long SRT, as discussed below. Additional information on temperature in septic tanks is discussed in Section 2.4.1.

Solids retention time (SRT) in anaerobic reactors is around 20 days for processes occurring at mesophilic temperatures (i.e., 30°C). The suggested SRT can be as high as 28 days at temperatures of 18°C, and as low as 10 d for processes occurring at 40°C (McCarty, 1964; Tchobanoglous et al., 2003). In a complete-mix digester (i.e., typical anaerobic digester) the SRT is the same as the HRT (Tchobanoglous et al., 2003). However, a septic tank is not a complete mix-reactor because sedimentation and solids accumulation processes are involved and result in a phase separation. It should be noted that limited intermittent mixing does occur in the sludge layer in a septic tank due to bubble formation and release.

Sludge accumulates in the septic tank for years between tank cleaning events, resulting in an extended SRT, while the design HRT in the tank is only 1 to 2 d (U.S. EPA, 2002). In a complete-mix anaerobic reactor, 60% of volatile suspended solids (VSS) are destroyed in 20 d (Tchobanoglous et al., 2003). Therefore, the VSS destruction in a septic tank is expected to be relatively high (e.g., 50%) due to the long SRT (see Appendix B).

Solids are removed from the tank periodically, usually in response to poor performance or when the volume of solids in the tank reaches a certain limit (see Table 2-3). At the time of cleaning, it is common to have the septic tank emptied fully without leaving sludge in the tank for seeding purposes (U.S. EPA, 2002). The material that is removed from the tank is known as septage. It should be noted that the solids contained in the septage range from old material accumulated since the previous tank cleaning event to material deposited immediately prior to cleaning. Thus, the SRT is approximately equal to one half of the time between tank cleaning events. A comparison of the operational parameters for a typical anaerobic digestion process and a septic tank is shown in Table 2-6.

2.3.3 Toxic Compounds in Anaerobic Reactors

There are many inorganic and organic compounds that at certain concentrations become inhibitory or toxic in anaerobic reactors. Toxic compounds can range from inorganic ions such as potassium, magnesium, or calcium, to metals such as copper, zinc, or lead (McCarty, 1964). In general, a toxic effect occurs at high concentrations. Conversely, at low concentrations, the effect of these compounds might be stimulatory and favorable to the anaerobic process (McCarty, 1964). Moreover, anaerobic conditions must be maintained in the reactor as even small amounts of oxygen inhibit methane forming microorganisms.

Earth metal salts commonly found in industrial wastes, such as sodium, potassium, calcium, or magnesium, are highly toxic, causing failure or low treatment efficiency (McCarty, 1964; Speece, 1996). It has also been reported that toxicity is related directly to the cation of the salt (i.e., Na^+) instead of the anion (McCarty, 1964). For example, in a septic tank study, Weibel et al. (1955) reported that a 1.2 % (12,000 mg/L) mixed salt brine representative of a water softener backwash cycle inhibited a non-acclimated anaerobic digestion process for 9.5 d. Weibel et al., (1955) also reported that digestion activity in acclimated sludge was not inhibited at

Table 2-6. Typical Operating Parameters for Single-Stage Complete Mix Anaerobic Digester and Septic Tank.

Parameter	Units	Single-stage complete mix digester	Septic tank
COD	$kg/m^3{\cdot}d$	3.2 - 32	0.07 – 0.106[a]
SRT	d	20	574 – 730[b,c]
HRT	d	20	1 – 2
Temperature	°C	30 - 38	7 – 30
Nitrogen	mg/g COD	5 – 15[d]	11[e]
Phosphorus	mg/g COD	0.8 – 2.5[d]	6.8[e]
Alkalinity	mg/L as $CaCO_3$	2,500 to 5,000	4,500
Mixing	-	Complete	Intermittent by bubble activity

[a] Calculated values, see Appendix A.
[b] Approximately equal to one half of the time between tank cleaning events.
[c] Cleaning event assumed every three to five years (D'Amato et al., 2008).
[d] Rittman and McCarty (2001).
[e] Based on typical raw residential wastewater values (Crites and Tchobanoglous, 1998; Höglund, 2001).

representative concentrations. Inhibitory as well as stimulatory concentrations of selected compounds are shown in Table 2-7.

Table 2-7. Cation Concentrations that Cause Inhibitory and Stimulatory Effects on Anaerobic Processes[a].

	Concentration, mg/L		
Cation	Strong inhibition[b]	Moderate inhibition[c]	Stimulatory
Na^+	8,000	3,500 - 5,500	100-200
K^+	12,000	2,500 - 4,500	200-400
Ca^{2+}	8,000	2,500 - 4,500	100-200
Mg^{2+}	3,000	1,000 - 1,500	75-150

[a] Adapted from McCarty, 1964.

[b] Concentration that slows down the anaerobic treatment resulting in low efficiency.

[c] Concentration that can be accepted with some microbial acclimation.

Ammonia and ammonium ion are also toxic compounds found in anaerobic reactors produced normally during the anaerobic degradation of proteins or urea, which are present in some industrial wastes and in concentrated municipal sludge (McCarty, 1964; Speece, 1996). The ammonia concentration depends on the pH and can be present as mostly as the ammonium ion (NH_4^+) at pH values below 7.25, or mostly as dissolved ammonia gas (NH_3) at higher pH values (McCarty, 1964). Concentrations reported as inhibitory vary from 1500 to 3000 mg/L ($NH_3 + NH_4^+$) and completely toxic at concentrations above 3,000 mg/L (Rittman and McCarty, 1964).

High sulfate concentrations can be problematic during anaerobic digestion processes because sulfate reducing bacteria (SRB) compete with methanogens for substrate (i.e., acetate) within the reactor. The activity of SRB can inhibit methanogens and increase the concentration of hydrogen sulfide (H_2S), which is toxic to the majority of the biomass. Hydrogen sulfide is a corrosive gas and its removal from the biogas is expensive (Winfrey and Zeikus, 1977; Schönheit et al., 1982; Isa et al., 1986; Parkin, 1990; Speece, 1996). Ranges of sulfate inhibitory concentrations reported in the literature are presented in Table 2-8.

Table 2-8. Inhibitory Sulfate Concentrations for Anaerobic Processes Reported in the Literature.

Sulfate concentration, mg/L	Reference
>100[a]	Winfrey and Zeikus, 1977
>200[b]	Patel et al., 1978
>50[c]	Parkin and Speece, 1982
>800[d]	Parkin and Speece, 1982
>145[e]	Parkin et al., 1990

[a] Analysis performed in freshwater sediments.

[b] Pure cultures of methanogens were growth in synthetic media.

[c] Value found in an unacclimated batch digester.

[d] Value found in a submerged anaerobic filter.

[e] Value found in an anaerobic chemostats for acetate systems.

In some cases, sulfate can also be favorable for anaerobic treatment. When sulfate is reduced to sulfide by microbial action, it can combine with and precipitate metals such as copper, nickel, or zinc as non-toxic materials, resulting in an effective approach to control metal toxicity (McCarty, 1964; Isa et al., 1986). McCarty (1964) reported that concentrations below 200 mg/L are not toxic to anaerobic digestion reactors. In septic tanks, the sulfide produced during anaerobic degradation follows common metal precipitation pathways, forming insoluble metallic sulfides (Crites and Tchobanoglous, 1998) as depicted on Figure 2-7. It should be noted that sulfate reduction in septic tanks is typically incomplete; thus, sulfate is commonly detected in septic tank effluent. The increased sulfate concentration of wastewater in septic tanks resulting from water usage ranges from 30 to 60 mg/L (Crites and Tchobanoglous, 1998).

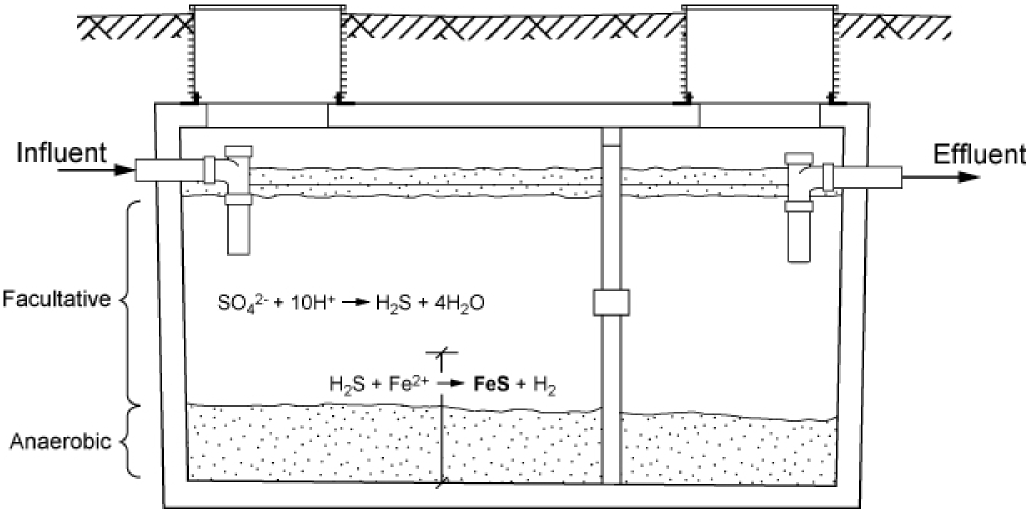


Figure 2-7. Sulfate Reaction with Metals in a Septic Tank.

Parkin et al. (1990), reported that sulfide is toxic in a range between 50 to 430 mg/L, with the toxic effects noticeable at the lower range. Moreover, Parkin et al. (1990) found that irreversible failure in anaerobic chemostats was noted at 62 mg/L for acetate systems and 60 mg/L for propionate systems. Conversely, Maillacheruvu and Parkin (1996) concluded that despite the sulfide toxicity, methanogenesis can still occur even in the presence of H_2S under specific conditions, such as high pH. Thus, it seems that sulfide dynamics and its effects on methanogenesis depend on microbial reduction, combination with metals, and pH levels within the anaerobic reactor. It is estimated that 1 mg/L of a sulfide salt such as sodium sulfide (Na_2S) is enough to precipitate soluble metals (McCarty, 1964). The weak sulfide complexes formed (i.e., FeS, highlighted on Figure 2-7) are not harmful to the microorganisms present in the sludge.

Finally, organic compounds such as alcohols and fatty acids can be toxic when fed to anaerobic reactors at high concentrations (McCarty, 1964). This situation is common when industrial wastewater is being treated; however, when the organic material is fed continuously, the anaerobic reactor acclimates and is able to handle the organic compound degradation (McCarty, 1964). Septic tanks used for the treatment of domestic wastewater are typically not subject to loading with concentrations of organic compounds sufficient to cause toxicity. In addition, the anaerobic reactions occurring in the sludge layer are buffered from toxicity associated with the liquid flowing through the tank.

2.4 Gas Emissions from Septic Systems

Even in the earliest literature on septic tanks, gas emissions have been a topic of interest. The formation of gases such as methane and carbon dioxide inside the tank are due to complex biological reactions, which are influenced by different factors such as temperature, loading, and season of the year. The focus of this section is on the factors affecting gas production, different techniques used to measure gas fluxes, and methane estimates from several sources that have reported septic tank gas emissions.

2.4.1 Gas Formation and Temperature Influence in Septic Tanks

The temperature inside a septic tank depends on the water use activities in the house and follows seasonal temperature changes according to geographic location. As shown on Figure 2-8a, in tanks located in the San Francisco Bay area, which has a temperate climate and little seasonal variation, the temperature follows the ambient temperature patterns, varying about 6 - 8°C throughout the year. However, as shown on Figure 2-8b and 2-8c for Quebec (Canada) and Kansas (U.S.), the temperature in septic tanks in more extreme climates is subject to higher seasonal variation than San Francisco.

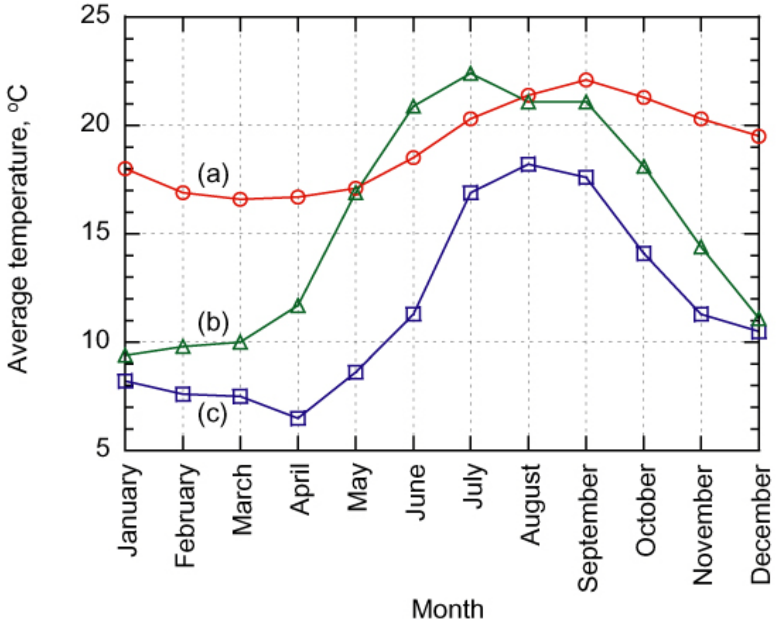


Figure 2-8. Average Monthly Temperature in Septic Tanks located in (a) San Francisco Bay Area, U.S. (Adapted from Winneberger, 1984); (b) Quebec, Canada (Adapted from Roy and Dubé, 1994) and (c) Kansas, U.S. (Adapted from Walker and Driftmier, 1929).

The gases formed during the anaerobic digestion process occurring within the sludge layer in the septic tank rise to the liquid surface or to the scum layer (if present). Settled solids accumulated on the bottom of the tank to which gas bubbles attach eventually become buoyant and rise to the surface to become part of the scum layer (Walker and Driftmier, 1929; Perking, 1989; Crites and Tchobanoglous, 1998).

The rate of gas formation inside the tank is related to temperature (Walker and Driftmier, 1929; Winneberger, 1984; D'Amato et al., 2008). Winneberger (1984) pointed out that septic tanks developed a temperature gradient from top to bottom. In the study, it was determined that warmer temperatures were located in the bottom and colder temperatures were found on the top. Based on the analysis and observations, temperature variation was correlated with hot water use in the house. In addition to the septic tank inner thermal stratification, seasonal temperature variation has also been reported (Walker and Driftmier, 1929; Winneberger, 1984; D'Amato et al., 2008), as shown previously on Figure 2-8. During cold months (winter), the rate of solids decomposition is reduced and the amount of solids build up in the bottom of the tank increases.

Conversely, in warmer months (spring) the degradation rate increases due to the elevated temperature in the accumulated solids. A sudden increase in the rate of anaerobic activity can result in a condition known as the spring turnover or spring boil (Winneberger, 1984; D'Amato et al., 2008). The increased gas production and the change in the solubility of the dissolved gases during the spring turnover results in a decrease in the solids removal efficiency due to the resuspension and discharge of settled solids. The gases also disturb the incoming solids and therefore inhibit their ability to settle (D'Amato et al., 2008).

2.4.2 Gas Collection Techniques and Chamber Systems

Theoretical estimates of gas fluxes from septic systems can be determined from the organic loading of the system or by models developed for this purpose (e.g., IPCC, 2006). Direct techniques to measure gas fluxes from septic tanks have rarely been reported in the literature (Walker and Driftmier, 1929; Winneberger, 1984). However, devices designed to measure gas fluxes from environmental systems (e.g., anaerobic ponds, wetlands, and agricultural soils) have been in use for a number of years.

Winneberger (1984) collected gas samples from septic tanks using submerged inverted bowls, which were placed inside seven tanks for several days. Subsequently, gas samples were taken and analyzed for methane, carbon dioxide, hydrogen sulfide, and other air components using standard techniques such as mass spectrometry and iodometry. One potential issue with this study is the long contact time between the collected gases and the liquid, potentially allowing for some of the gases to partition into the liquid following Henry's Law, and thus impact the relative concentration of the gases analyzed.

Measurements of gases using floating platforms with gas-collection domes or chambers have been used to determine methane fluxes in anaerobic lagoons and wetlands (Moore and Roulet, 1991; DeSutter and Ham, 2005; Aneja et al., 2006). An example of a flux chamber design to measure gas fluxes from soil-plant systems is depicted on Figure 2-9.

The method used in each study depends on the particular conditions of the systems analyzed and the research objectives. While the gas sampling methodology is highly specific to the particular system under assessment, the chamber configuration and design have certain parameters in common. Typically, non-reactive materials are used to fabricate the body of the chamber, with stainless steel and PVC being used most frequently. Teflon tubing is recommended for vents and sampling lines to minimize chemical reaction and temperature rise. Moreover, the incorporation of a small fan to mix the headspace of the chamber is seen in almost all the flux measurement devices. For those devices located in outdoor environments, an insulated cover is used to diminish temperature alteration inside the chamber headspace (Moore and Roulet, 1991; Hutchinson and Livingston, 1993; USDA-ARS, 2003; DeSutter and Ham, 2005; Aneja et al., 2006).

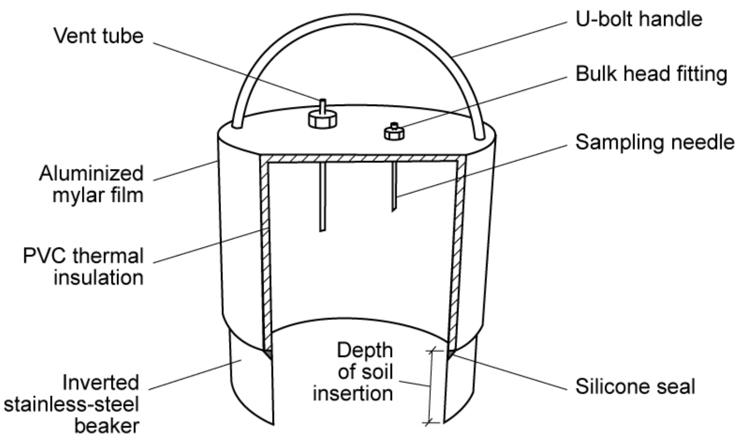


Figure 2-9. Flux Chamber Designed by the USDA-ARS GRACEnet to Measure Gas Fluxes from Soil Systems. Note the Venting Tube and PVC Materials are Common Features in Flux Chambers.
Adapted from Chamber-Based Trace Gas Flux Measurement Protocol. USDA-ARS GRACEnet, 2003.

Moore and Roulet (1991) used both open (dynamic, forced flow-through air circulation) and closed (static, no forced air exchange) flux chambers; methane fluxes were determined by means of gas chromatography (GC). From a comparison between the two types of chambers it was found that the methane fluxes may be underestimated using the static chamber by 20%. Nevertheless, the researchers suggested that statistically, the difference in performance is relatively small. The static chambers were recommended for measuring regional estimates of methane fluxes because they can be economical and low-maintenance compared with the dynamic chambers.

Hutchison and Livingston (1993) discussed that both types of chamber systems (dynamic and static) are subject to bias from physical and biological factors during the measurement process; and suggested some corrective actions according to the source of the bias. For example, to minimize pressure effects, Hutchison and Livingston (1993) recommended the use of an open tube to evacuate the air from the chamber when it is first installed. According to Hutchinson and Livingston (1993), there is not a preference to use one chamber system or the other. However, it was noted that the chamber used should be adapted to the particular environment and sampling conditions, taking into account factors such as temperature, season, atmospheric pressure, soil type, irrigation frequency, and wind.

Based on comparisons between open and closed flux chambers and spectroscopic techniques such as fourier transform infrared (FTIR) spectroscopy and tunable diode laser spectroscopy (TDLSS) to measure nitrous oxide fluxes from two soil-plant systems, it was concluded that there was a good agreement and no bias in the data was obtained with the different methodologies (Christensen et al., 1996).

2.4.3 Results from Previous Gas Measurement Studies

Gas fluxes from septic tanks have rarely been measured. Winneberger (1984) studied seven septic tanks for a ten month period. Gas samples were collected and analyzed for carbon dioxide, hydrogen sulfide, and methane, as well as other atmospheric components such as argon, oxygen, nitrogen, and hydrogen. Winneberger (1984) determined that gas measurements of carbon dioxide and hydrogen sulfide varied greatly from tank to tank. However, it was reported that methane values were more consistent, ranging from 66.3 to 88.7% by volume, with a mean of 72.9%. The highest methane value reported was in the hottest month, therefore, it is possible that the amount of gas increased due to the enhanced sludge degradation. Some important observations reported in the Winneberger (1984) study were:

- Gases formed by the sludge degradation over the tank bottom were uniformly produced.
- Gases filled up the headspace of the chamber collector apparatus in two days.
- The gas flux estimated per capita in one tank was 28 L/capita·d.

In a study conducted by Philip et al. (1993), an attempt was made to measure methane production from 50 septic tanks during a three yr period in Southern France. To analyze the methane production potential from the sludge, samples were withdrawn and placed at 20°C for three weeks. In this case, the gases were not collected directly from the septic tank by means of flux chambers or similar devices. During the third year of the study, methane production was found to have increased by a factor of five compared to the first two years. The authors concluded that the degradation of VFA and hydrolysed compounds increases after the second year due to the decline of COD. Unfortunately, the study does not go into detail on the causes of the change in gas production and no data are provided on individual septic tank gas fluxes.

Globally, it is believed that nitrous oxide (N_2O) emissions also come from various types of solid waste and wastewater management practices, including pit latrines, composting toilets, septic tanks, and engineered systems, including activated sludge, trickling filters, anaerobic or facultative lagoons (Bogner et al., 2007). These N_2O emission rates are expected to be reduced through implementation of mitigation technologies such as landfill gas recovery, improved landfill practices, engineered wastewater management, controlled composting and expanded sanitation coverage in countries under the Kyoto Protocol, especially in Asia, Africa, South America and the Caribbean (Bogner, 2007). Moreover, in an N_2O emission study developed by U.S. EPA (1999) on septic tanks and latrines in developing countries around the world, it was concluded that nitrous oxide contributions from these types of systems are probably not a significant source.

In the United Stated, a majority of nitrous oxide (N_2O) emissions are generated as a result of agricultural practices (U.S. EPA, 2009). While considered to be a relatively minor source, N_2O emissions are also generated in wastewater treatment as an intermediate product during nitrification and denitrification processes. Nitrous oxide formation is promoted by conditions of reduced aeration, high moisture, and abundant nitrogen in the form of urea, ammonia, or proteins (Bogner et al., 2007; U.S. EPA, 2009). Little specific data on emissions from septic systems have been reported in the literature, however, it is expected that nitrification and denitrification of septic tank effluent in soil-based dispersal systems could potentially result in some N_2O emissions.

2.4.4 Estimates of Methane Production

To address the lack of studies on direct measurements of GHG emissions from septic tanks, it is necessary to calculate emission values that might represent a baseline for comparison when empirical values are obtained. Estimates of methane emissions can be developed based on an organic loading approach, where it is assumed that in the United States, one person discharges 200 g/d of COD (Crites and Tchobanoglous, 1998) and that 60% of the influent COD is reduced due to settling and anaerobic digestion inside the septic tank. Based on this calculation approach, the theoretical methane production is 11.0 g CH_4/capita·d (see Appendix B for calculations). It should be noted that this calculation approach accounts for the COD that is eventually removed from the system as septage.

Kinnicutt et al. (1910) reported methane measurements from community septic tanks in Lawrence, MA in the early 1900's. Studies from Kinnicutt et al. (1910) describe the significant relation that exists between the methane emissions from septic tanks and the temperature. As shown on Figure 2-10, values around 8-12°C have corresponding methane emission rates in the range of 0.1 to 2 g CH_4/capita·d. Alternately, temperatures values ranging from 16-20°C, have reported methane emission rates ranging from 3-6 g CH_4/capita·d. Thus, the reduction of gas emissions in the cold months was clearly observed. Conversely, as shown on Figure 2-11, in hot months an increase in gas release was observed. Kinnicutt also observed that gas production from septic tanks started almost immediately during warm months, while in cold months gas production was delayed until the tank contents warmed in the spring and summer. Thus, tanks that were emptied in the winter had the anaerobic digestion process inhibited by temperature.

Winneberger (1984) estimated 22- 28 L/capita·d of gas from a single septic system. Assuming that, as reported, the gas was 70% methane and a methane density of 0.67 g/L CH_4 results in an emission rate range from 14- 18 g CH_4/capita·d. Similarly, based on the method developed by the IPCC (1996, 2006), methane emissions from a domestic septic tank are approximately 25.5 g/capita·d (see Appendix C for calculations). However, as noted in Appendix C, the IPCC method uses an assumed methane conversion factor (MCF) of 0.5 to represent the conversion of organic matter to methane. A summary of the different methane emission rates estimates is presented in Table 2-9.

Table 2-9. Estimates of Methane Emission Rates from Septic Tank Liquid Surface.

Method	Year	Methane estimate (g CH_4/capita·d)
Kinnicutt et al.	1910	10.1[a]
Winneberger	1984	14 to 18[a]
COD loading	2009	11[b]
IPCC	2007	25.5[c]
Sasse	1998	18[d]

[a] Measured value.

[b] Calculated value assuming that 40 % of solids are removed as septage (see Appendix B).

[c] Calculated value assuming that half of the influent COD is converted anaerobically (see Appendix C).

[d] Calculated value assuming 25 % CH_4 dissolved (see Appendix D).

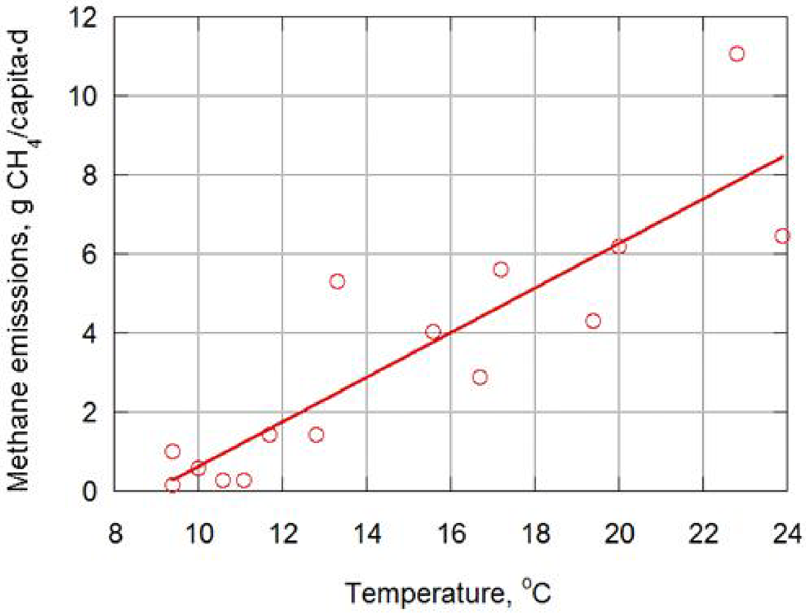


Figure 2-10. Relationship between Methane Emission Rates from Liquid Surface of Community Septic Tank and Water Temperature.
Kinnicutt et al., 1910.

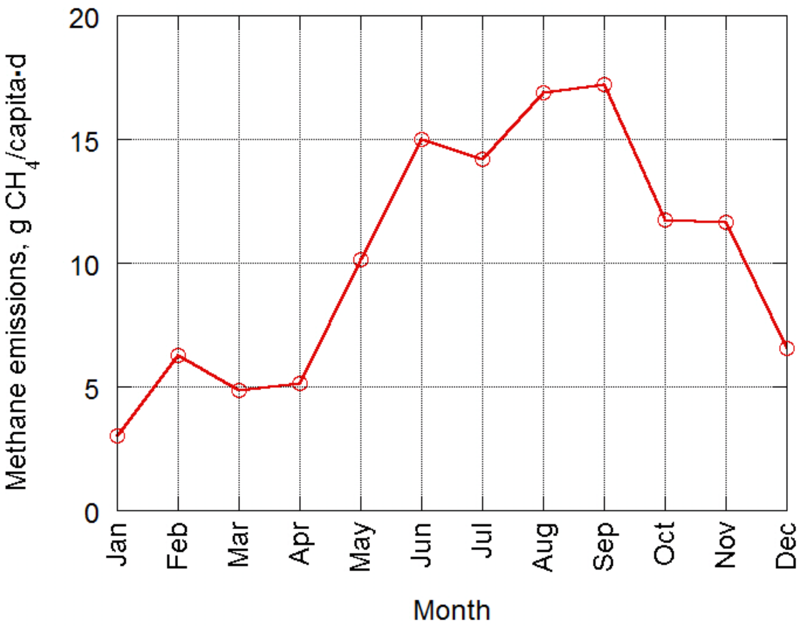


Figure 2-11. Monthly Methane Emission Rate from Liquid Surface of Community Septic Tank.
Kinnicutt et al., 1910

Sasse (1998) presented a model for estimating gas production from a septic tank system based on tank configuration, loading, temperature, and other variables. Using the Sasse (1998) model and typical values for North American septic tank design, loading, and configuration, a total methane production value of 18 g CH_4/capita·d is calculated (see Appendix D). The Sasse model also accounts for methane that leaves the tank in the effluent. For purposes of the calculation, it was assumed that 25% of the methane produced leaves the tank dissolved in the effluent.

2.4.5 Gases in Effluent Dispersal Systems

In soil-based effluent dispersal systems, wastewater is applied typically using a system of perforated pipes. At the point where septic tank effluent is applied to the soil, a clogging zone occurs as a result of high moisture content and excess organic matter. The clogging zone is composed of various materials, including wastewater particulate matter, microbial biomass, and inorganic precipitates. Based on oxygen diffusion rates alone, it has been determined that the supply of atmospheric oxygen is a limiting factor (Janna, 2007; Erickson and Tyler, 2001). Thus, the development of anaerobic conditions and clogging zones in conventional soil dispersal systems is an expected phenomenon.

2.5 Summary of GHG Emissions from Wastewater Systems

The increase in carbon dioxide and other gases in the atmosphere have motivated entities, such as the IPCC, to build GHG inventories to determine critical emitting sources. The published studies on GHG emissions from wastewater treatment plants and the relative importance of septic tanks gas emissions are summarized in this section.

2.5.1 Observations of GHG Emissions from Wastewater Treatment Plants

Concern about climate change has resulted in increased research on the emission of GHGs to the atmosphere (IPCC, 1996; U.S. EPA, 2006; Sahelli, 2006; Chandran, 2009; Foley and Lant, 2009). In general, onsite wastewater treatment systems have received less attention compared to full-scale wastewater treatment plants when accounting for GHG releases. However, it is important to have an understanding of the GHG estimated in these studies and the different approaches used to obtain them. Sahely (2006) used a life cycle assessment methodology to quantify GHG emissions from municipal wastewater treatment facilities in Canada, reporting carbon dioxide as the major gas contributing to GHG emissions, due to the predominance of aerobic treatment processes. It should be noted that life cycle assessment (LCA) studies are highly influenced by the boundary conditions and individual assumptions; consequently the findings should be considered only as a baseline for emissions inventories.

Foley and Lant (2009) published an experimental approach to evaluate gas fluxes from WWTPs in Australia. The study focused on the estimation of methane and nitrous oxide emissions from four full-scale treatment systems. The researchers pointed out that the estimated methane emissions from wastewater collection systems are underestimated and suggested that models should be developed to address this situation. Liquid methane measured at the inlet and outlet of various WWTPs are summarized in Table 2-10.

Cakir and Stenstrom (2005) developed a mass balance model to compare methane and carbon dioxide gases from aerobic and anaerobic wastewater treatment systems. The aerobic technology studied was a conventional activated sludge process and the anaerobic technology was an upflow anaerobic sludge blanket (UASB) reactor. It was reported in the study that aerobic processes release less GHG than anaerobic treatment processes for low strength (~300 g/L) influent BOD_u (ultimate carbonaceous oxygen demand or 20 d BOD). According to the model, for a BOD_u concentration of 100 mg/L, the dissolved methane in the effluent of the UASB was around 84 mg CH_4/L, while it was just 0.26 mg CH_4/L at the effluent of the aerobic process. The authors suggested that capturing the liquid methane produced after the UASB treatment was an alternative to reduce the total GHG emissions from the anaerobic treatment.

Table 2-10. Summary of Dissolved Methane Measured at Three WWTPs in Australia (Foley and Lant, 2009).

Wastewater system	Location	Flow m^3/d	Inlet, mg CH_4/d	Outlet, mg CH_4/d
Lagoons[a]	Adelaide Hills, South Australia	1,200	3.2 – 7.2[d]	0.3 ± 0.2
CAL[b]	Melbourne, Victoria	230,000	0.5 - 1.5[e]	0.7 ± 0.4
PST[c]	Sydney, New South Wales	275,000	0.5 – 1.5[e]	0.6 ± 0.1

[a] Uncovered anaerobic/facultative lagoons.
[b] Covered anaerobic lagoon.
[c] Primary sedimentation tank.
[d] Raw wastewater received via a rising main.
[e] Raw wastewater received by gravity.

2.5.2 Relative Importance of the Septic Tank Gas Emissions

Wastewater treatment systems are estimated to account for about 4% of the total methane emissions in the U.S. and are also a source of nitrous oxide, another GHG with an equivalent effect of more than 296 times that of carbon dioxide (IPCC, 2007; U.S. EPA, 2009). Using the IPCC methodology, the U.S. EPA (2009) has determined that a majority of the methane emissions associated with wastewater originate from onsite septic systems, due to the uncontrolled release of methane to the atmosphere and the large numbers of individual septic systems in use. According to the U.S. EPA (2010), methane and nitrous oxide emissions from all domestic wastewater systems are 15.7 and 4.9 Tg CO_2e/year, respectively. Using the U.S. EPA (2010) approach, the total methane emissions from septic systems is about 12.8 Tg CO_2e/year and nitrous oxide emissions are not accounted for. Methane and nitrous oxide emissions attributed to centralized wastewater treatment are about 2.9 and 4.9 Tg CO_2e/year, respectively. It should be noted that energy and chemicals used in collection and treatment, as well as gas emissions associated with wastewater collection, are not accounted for in the U.S. EPA (2010) emissions model.

Given the data presented in Table 2-9, there is a significant difference in the previously measured methane emission values compared to the IPCC model estimates; thus, there is reasonable justification to conduct additional studies to quantify the amount of gases released to the atmosphere from septic tanks. The U.S. EPA (2010) model used to determine GHG emissions from septic systems applies the same methane correction factor, MCF (see Appendix C) used in the IPCC model, therefore both models result in the same estimate of methane emissions (see Table 2-9). Again, the MCF value of 0.5 used in the U.S. EPA (2010) model is based on the assumption that half of the influent organic matter is converted to methane.

CHAPTER 3.0

MATERIALS AND METHODS

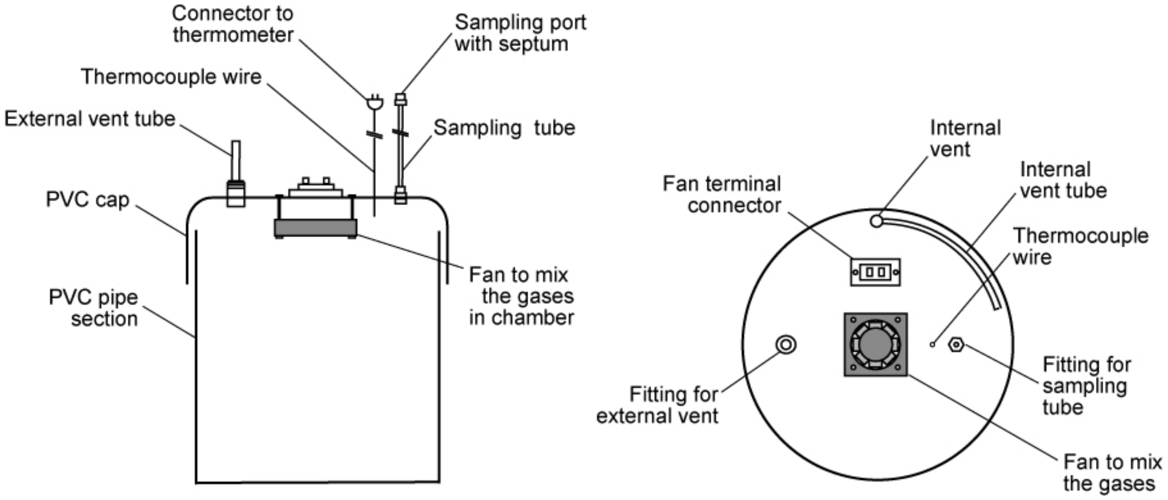
The topics presented in this section include the design of the devices and protocols used for sampling at the (a) septic tank liquid surface, (b) venting system, and (c) soil dispersal system; GHG laboratory analysis methods and procedures; factors taken into account for data quality control and data acquisition; and equations used for data analysis.

3.1 Design of Sampling Devices

This section presents a description of the flux chamber designed for use in the septic tanks, the modifications made to the flux chamber for use in the soil dispersal systems, and the device designed to obtain gas samples from the venting system.

3.1.1 Flux Chamber Design for Use in Septic Tanks

Measurements of GHG emissions from soil-plant systems using flux chambers and the corresponding sampling techniques are well established (Hutchinson and Livingston, 1993). However, little information is available on gas flux measurements from the liquid/solid surface of septic tanks. Thus for this research, a flux chamber design based on the soil-plant system was modified, constructed, and tested, along with the development of a corresponding sampling methodology. The flux chamber is shown on Figure 3-1.



(a) (b)

Figure 3-1. Flux Chamber Developed to Sample Gases from Liquid Surfaces: (a) Side View of the Flux Chamber and (b) Internal View of the Flux Chamber Where the Fan and Internal Vent are Visible

The main body of the flux chamber was constructed from a PVC pipe section (12" diameter, 12" length), inserted into a 12" diameter PVC cap. A 12-volt fan was installed inside of the cap to ensure that the gases were well mixed in the chamber. A 3/16" brass Swagelok fitting was inserted into the PVC cap to hold 4' of Teflon tubing (3/16" external diameter). A second brass piece at the end of the tubing was fitted with a septum to comprise the sampling port used to withdraw the gas samples. Two additional vinyl tubing vents were installed, one being a 1/4" internal vent that extended 8" inside of the cap and one a 1/2" diameter external vent of 6' in length with a valve at the end as seen on Figure 3-1b.

The purpose of the vents was to maintain atmospheric pressure inside the chamber. The larger vent was only used while initially submerging the flux chamber into the liquid to account for the large amount of air that needed to be displaced. The larger vent was closed after the flux chamber was in position for sampling. The total gas volume inside of the flux chamber during sampling was determined using a scale fixed to the side of the chamber; the scale was used to measure the depth of the chamber submergence. The chamber was suspended in the tank from an above ground tripod using chains attached to the cap.

3.1.2 Flux Chamber Inserts for Septic Tanks

A tank insert designed and used to prevent disturbance of the septic tank contents and to support the flux chamber when measurements were being taken is shown on Figures 3-2 and 3-3. This insert was necessary when there was a scum layer present on the liquid surface. The insert was composed of a 10" diameter PVC pipe section with a length of 8" with a channel at the top. The insert was supported with PVC legs going to the bottom of the tank, such that the insert was submerged about 6" into the liquid in the tank. The channel was filled with water prior to sampling. The flux chamber was lowered into the water filled channel to seal the contents of the chamber. The tank inserts were left in place for the duration of the experiment. Some tanks had limited access and it was not possible to fit the 12" flux chambers inside the risers; therefore a 6" diameter flux chamber and inserts of the same diameter were built to address this situation. A summary of the chamber size use per site and compartment is shown in Table 3-1.

Table 3-1.Chamber Size Used in Each Site by Septic Tank Compartment.

Septic tank compartment	Diameter of flux chamber used at each site (inch)							
	1	2	3	4	5	6	7	8
First	6	6	6	6	12	6	6	6
Second	6	6	12	12	12	6	6	6

(a) (b)

Figure 3-2. Example of Insert Used for Gas Sampling from Septic Tanks with Scum Layer: (a) View of 6 and 12 inch Inserts and (b) Close-up View of the 12 inch Insert.

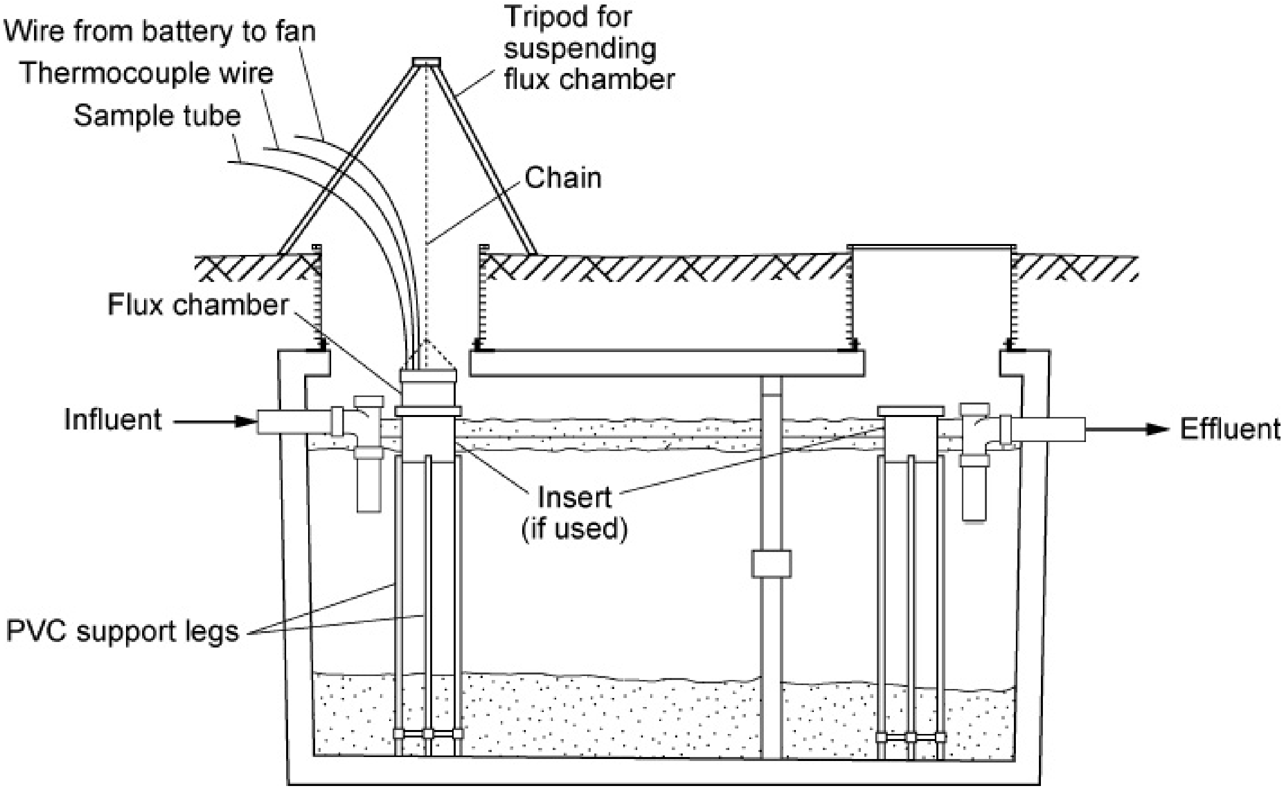


Figure 3-3. Sampling Device Used to Obtain Gas Samples Through Scum Layer. Note the Placement of the Flux Chambers and Inserts.

3.1.3 Flux Chamber Design for Use in Soil

A chamber similar to that described in Section 3.1.1 was constructed to take samples from the leach field (Hutchinson and Livingston, 1993, USDA-ARS, 2003). The key difference between the leach field and septic tank flux chambers is that the leach field chamber did not include the external vent and it had an additional covering of reflective insulation (as seen on Figure. 3-4) to decrease the sensitivity of the measurements to radiant heating.

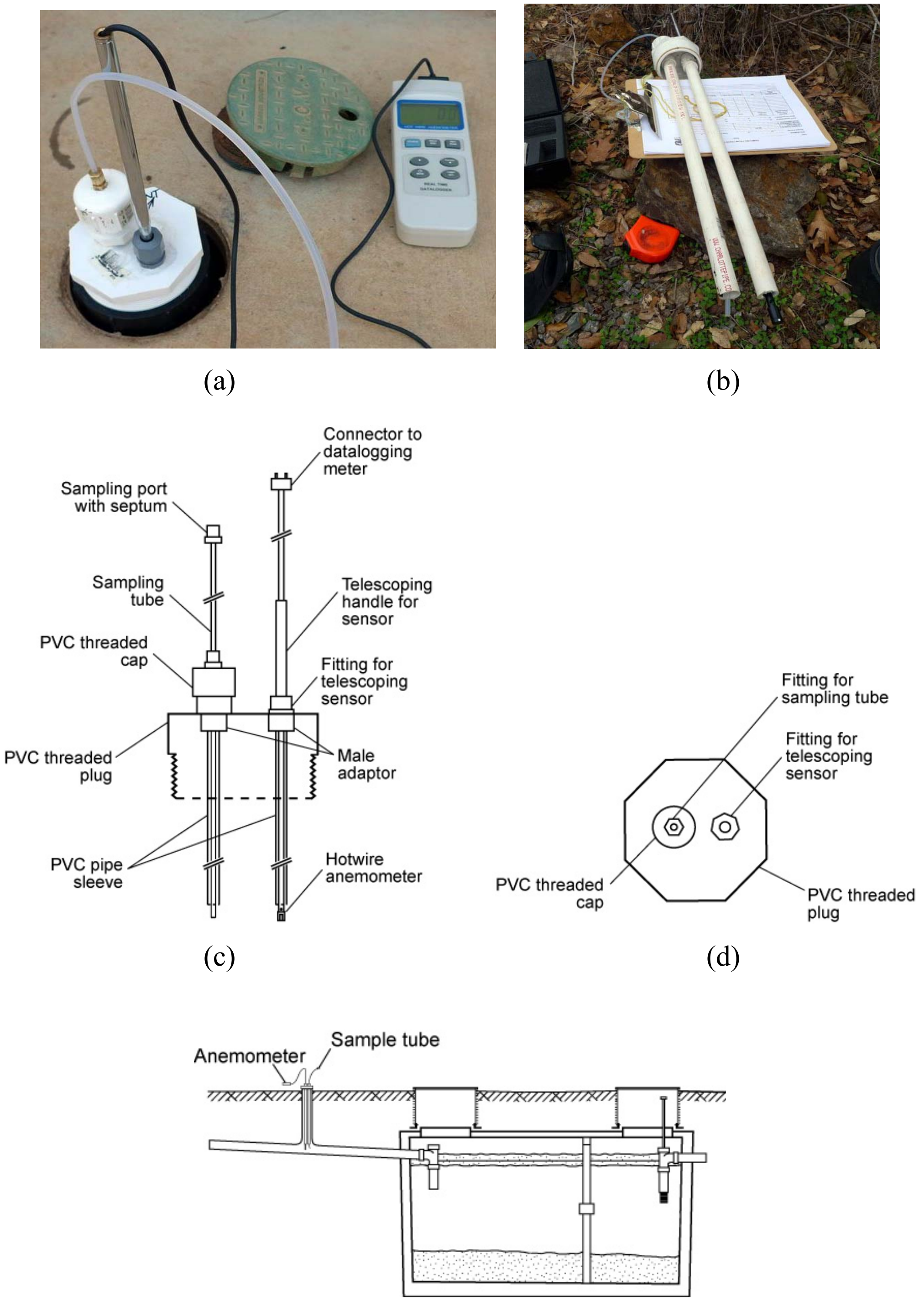
Figure 3-4. Flux Chamber Designed for Testing Gases from the Leach Field.

3.1.4 Flux Chamber Inserts for the Soil

The inserts for the soil dispersal system were made of PVC pipe (12" diameter and 4" length). The soil inserts were functionally similar to the scum layer inserts described above. Six inserts were installed above each soil dispersal system a week in advance to the first sampling event in the soil. The insert pieces were left in the soil over the entire sampling period to minimize disturbances of the soil when the flux chambers were set and the samples taken (USDA-ARS, 2003).

3.1.5 Vent Sampling Device

An apparatus was built to sample vented gases from the septic system cleanout port. As shown in Figure 3-5, the sampling device consisted of a 3 or 4" PVC slip cap and threaded ABS adapter as needed to fit the cleanout port. Teflon tubing and a hot wire anemometer with a telescoping handle were mounted on the cap. A 3/16" brass Swagelok fitting was used to hold the Teflon tubing in place. A second brass piece at the end of the tubing was fitted with a septum for extraction of the gas samples with a syringe. A 1/2" cord-grip connector was attached to the cap to hold the hot wire anemometer (See Figure 3-5). Lengths of 1/2" PVC pipe sleeves were attached to the bottom of the cap with threaded adapters and used as guides for the sampling tube and the hotwire anemometer. The length of the PVC pipe sleeves varied depending on the depth to the same location at the centerline of the drain line as seen in Figure. 3-5. The device fit tightly in the clean out port, creating a tight seal. Because the cleanout was completely sealed when the gas sampling apparatus was in place, gases were constantly moving through the drain line of the house and exiting the building vent as would occur under normal conditions. The sample tubing and anemometer were small relative to the cross-sectional area of the drain line and therefore not expected to impact the gas flow.



(a) (b) (c) (d) (e)

Figure 3-5. Device Developed to Sample Gases from the Cleanout Vent (a) Main Body of the Device and Anemometer (b) View of the PVC Pipes Sleeves, (c) Profile and (d) Plant of the Vent Sampling Device. Not at Scale, and (e) Illustration of Technique Developed to Sample Vent Gases.

3.2 Sampling Protocols

The three principal components of an onsite wastewater treatment system were individually sampled to determine the GHG emissions. Each component had specific characteristics requiring a different sampling method. The following section contains descriptions of the sampling method developed for the septic tank liquid surface, the venting system, and the soil dispersal system. In addition, the technique used to obtain samples of dissolved methane is described.

3.2.1 Sampling Method for Liquid Surfaces

To sample at the liquid surface, the septic tank access port was opened and a tripod was set up to suspend the flux chamber (see Figure 3-6). The sample was obtained by submerging the chamber in the liquid. If a scum layer was present, an insert was installed prior to obtaining samples (see Section 3.1.2, Figure 3-2 and Figure 3-3).

1. The flux chamber was slowly submerged partially into the water. The chamber depth was recorded in every sampling event to allow later calculation of chamber volume. A complete water seal around the chamber was maintained to ensure accurate flux measurements. When the chamber was put into the water, the timer was started.

(a) (b)

Figure 3-6. Use of Flux Chamber for Gas Sampling from Septic Tank Located in Cool, CA (a) Deployment of Flux Chamber Into First Compartment of 1200 Gallon Septic Tank and (b) Extraction of Headspace Sample from Flux Chamber Using Syringe.

2. A 12 mL syringe was inserted into the sampling tube septum and 6 mL of volume was taken and discharged into the air (see Figure 3-6). This step was used to purge the accumulated gases in the sample line, which had a volume of 6 mL. Simultaneously, a temperature reading was obtained.
3. After purging the sample line, two 12-mL samples were collected and put into one of the previously evacuated vials to obtain a total sample volume of 24 mL (vial evacuation

procedure is shown in Appendix E). The vial was labeled and protected from the sun. For the initial (t = 0) sample, the fan was not needed because a concentration gradient had not developed.

4. The time interval between samples was 10 min. Before withdrawing further samples, the fan was energized briefly (5 sec) to mix the contents of the flux chamber. At time 10 min, the fan was turned off and the second sample was collected after purging the sample line again. Again the temperature inside the chamber was recorded.
5. Step 4 was repeated for the third sample. The flux chamber was then taken out of the water and the access port closed and secured.

3.2.2 Sampling Method for Soil Systems

1. Five 12 inch PVC permanent inserts were inserted at different locations in the leach field area and another one was placed outside the leach field to use as a control site. The permanent inserts were used to hold the flux chambers while gas measurements were taken; the inserts remained in place for the duration of the study. These pieces have a similar design to the insert used for sampling through the scum layer (Figure 3-7); however they were shorter (6 or 4" in length). As with the scum layer sampling, a water seal was applied, creating a complete seal between the insert and the flux chamber.

(a) (b)

Figure 3-7. Use of Flux Chamber in the Soil Dispersal System (a) Permanent Insert and (b) Extraction of the Headspace Sample from the Flux Chamber.

2. The flux chamber was placed on the inserts sealing them together and avoiding any gas leakage during sampling.
3. The 12 mL syringe was inserted into the sampling septum and used twice to withdraw a total sample volume of 24 mL at time zero; the overall process was similar to the liquid surface measurements described above. After discharging the samples into a previously evacuated vial, a temperature reading was obtained.
4. The time interval between samples was 10 min. Before withdrawing the next samples, the fan was energized briefly (5 sec) to mix the contents of the flux chamber. At time 10 min, the fan was turned off and the second sample was collected. Again the temperature inside the chamber was recorded.
5. Step 4 was repeated for the third sample after which the flux chamber was taken out of the insert piece.

3.2.3 Sampling Method for Vent System

1. The cap of the cleanout port located before the septic tank was removed to verify that there was no water flowing through the pipe to avoid damaging the hot wire anemometer.
2. The length of the anemometer as well as the sampling line was adjusted to make sure that it was placed exactly in the middle of the pipe (see Figure 3-5).
3. The sampling device was installed in the cleanout port and the anemometer was turned on.
4. The 12 mL syringe was inserted into the sampling septum (Figure 3-8) and used twice to withdraw a total sample volume of 24 mL into an evacuated vial, as above. An air velocity reading was made each time a sample was taken.
5. Two more samples were taken following step four with a sampling interval of two min between them. Finally, the sampling device was removed and the cleanout cap was replaced.

Figure 3-8. Sampling of Gases from the Venting System.

3.2.4 Sampling Method for Aqueous Methane

1. Plastic tubing attached to a 12 mL syringe was inserted to approximately the middle of the liquid column in the first compartment of the tank.
2. Two full syringes of wastewater were withdrawn to purge the tube line. A final 12 mL sample was taken. Five mL of this sample were inserted into an evacuated vial. Then the syringe was pulled out leaving the hypodermic needle inside the septum for 30 sec to equilibrate the sample to ambient pressure (Alberto et al., 2000). A second 5 mL sample was drawn.
3. The plastic tubing was then inserted in the middle of the liquid column of the second compartment and step two was repeated.
4. After returning the samples to the laboratory, all the samples were shaken for 24 hours (Guisasola et al., 2008) to let the methane equilibrate between the liquid and gas phases.

5. The headspace gases were extracted from the vial using a syringe with a needle and placed in an evacuated tube for later GC analysis.

3.2.5 Sampling Method for Water Temperature

Thermocouples were attached at 12" intervals to a PVC pipe (1" external diameter with a total length of 7'). After the gas samples from the liquid surface were taken the following steps were performed.

1. The pipe was carefully inserted in the first compartment of the septic tank.
2. The thermocouple connectors were plugged to a thermometer reader and the temperature readings were recorded.
3. Steps 1 and 2 were repeated for the second compartment.
4. The pipe was pulled out from the second compartment and rinsed with water.

3.2.6 Sampling Method for Water Quality

A Myron L Ultrameter II^{TM} was used to measure dissolved solids, pH and redox potential. The water quality measurement procedure for these three parameters was as follows:

1. Vinyl tubing attached to a 20 mL syringe was inserted into the middle of the water column in the first compartment of the septic tank.
2. The syringe was purged with liquid from the tank twice. The liquid was returned to the septic tank.
3. The syringe was used to place liquid into the Ultrameter II^{TM} cup cell after which the reading was recorded. The liquid was poured back into the septic tank.
4. The syringe was filled again and 10 mL of wastewater was poured into a 12 mL plastic vial taken back to the laboratory for COD analysis. A HACH DR-890 colorimeter was used for the COD analysis, applying a COD digestion method. (U.S. EPA, 1993)
5. Steps 1 to 4 were repeated for the second compartment of the septic tank.

3.2.7 Sludge and Scum Thickness

1. A Sludge Judge sampling device (Nasco Equipment, Inc., Fort Atkinson, WI) was inserted until it reached the bottom of the septic tank.
2. The sampling device was pulled back from the tank bottom and the sludge thickness was recorded (see Figure 3-9).
3. The scum thickness was estimated using the same sampling device and feeling the scum thickness using the end of the probe. The measurement was recorded.
4. The sampling device was rinsed with water.

3.2.8 General Observations

Field observations were recorded during every sampling event on previously prepared forms (see Appendix F) designed for each system component. General observations on the septic tank scum appearance, presence of invertebrates, changes in the wastewater color and distinctive episodes such as turnover events and laundry water discharges were the most common aspects observed.

3.3 Gas Analysis

The gas samples were analyzed by a Shimadzu gas chromatograph (Model GC- 2014) with a 63Ni electron capture detector (ECD) linked to a Shimadzu auto sampler (Model AOC-5000). The samples were analyzed for CH_4, CO_2 and N_2O. The autosampler uses a gas-tight syringe to remove 5 mL gas from a sample vial and inject it into the GC port. The instrument was operated by experienced technicians with specialized training using a well established analytical protocol at the geochemistry laboratory of the UC Davis Plant and Environmental Science Department.

Figure 3-9. Sludge Measurement Taken at Site 4. The Red Marks are Located Every Foot.

3.4 Quality Control for the Samples

Before each sample event, one person from the research team was in charge of evacuating the vials and placing a mark on the vial's cap each time the vial was evacuated. After three subsequent evacuations, the septum inside the cap was replaced. All vials were labeled with the date and a code for each site prior to the sampling event (i.e., Septic Tank 1, inlet, time = 0 was labeled ST1 in 0).

During each sampling event one person from the research team was designated to be in charge of handling the samples taken on that particular day including protecting them from sun exposure, breakage or damage and delivering them to the laboratory for analysis.

The laboratory technicians were provided with three days of advance notice of the sampling event via e-mail to ensure that the GC was available and working properly. The laboratory technicians were responsible for measuring the CO_2, CH_4, and N_2O concentrations in the samples as well as the gas standards (two standards of each concentration per 24 samples) and submitting the results to the project manager. The system was calibrated daily using analytical grade standards (Airgas Inc., Sacramento CA). The quality of the samples was insured by using controls treated (age and storage conditions) the same as the field samples. Sample collection in the field and analysis of samples by GC was performed according to clearly established protocols.

3.5 Data Analysis

To calculate the gas fluxes from each component of the septic system, the data generated in the GC was analyzed based on different approaches. The calculation approach used in the septic tank, soil dispersal system and venting system is presented in this section.

3.5.1 Data from Septic Tank Analysis

The septic tank data were analyzed based on an algebraic linear model describing the gas flux rate coming into the headspace of the flux chamber. The gas flux was calculated using the slope of the trace gas accumulation curve from the measurements taken at each compartment of the septic tank during the sampling event. A sample plot for methane and carbon dioxide showing the linear fit for one flux measurement is presented in Appendix G. The equations used to calculate the septic tank flux values are shown below in Eq- 3-1 and Eq. 3-2. As shown in Eq. 3-1 the concentration in ppm (raw data from laboratory) were first converted to concentration in mg/m^3.

$$Gas\ concentration\,(mg/m^3) = \frac{(C_{ppm}/10^6)(MW)(1000\ mg/g)}{\left(\frac{RT}{P}\right)} \qquad \text{(Eq. 3-1)}$$

Where C_{ppm} is equal to concentration in ppm, MW is the molecular weight of the gas under consideration (g/mol), R is the gas constant (0.000082057 atm·m^3/mol·K), T is the absolute temperature (K), and P is the absolute pressure of the gas (atm). The concentration values (in mg/m^3) from individual measurement events (typically 4 to 5 consecutive samples) were then plotted as a function of time (See Appendix G). The slope m, in units of mg/m^3·sec derived from a linear fit of the data is then used to compute the flux using Eq. 3-2.

$$Flux\,(g/capita\cdot d) = \frac{(m)(V_{FC})(A_{comp})(86400\sec/d)}{(1000\,mg/g)(SA_{FC})(capita)} \qquad \text{(Eq. 3-2)}$$

Where m is the slope of a linear fit to the gas concentration data (mg/m^3·sec), V_{CF} is the volume of the flux chamber (m^3), A_{comp} is the liquid surface area of the compartment of the septic tank where the sample was taken (m^2), SA_{FC} is the liquid surface area occupied by the flux chamber (m^2), and capita is the number of occupants in the house.

3.5.2 Data from the Soil Dispersal System

A non-linear model (Hutchison and Livingston, 1993) was applied to account for gas production and consumption in the soil based on diffusion theory. The concentration values in ppm (raw data from laboratory) were first converted to concentration in mg/m^3 using Eq. 3-1. Equation 3-3 was then used to determine the gas flux rate from the soil dispersal system.

$$Flux\,(mg\,/\,m^2\cdot d)=\frac{V(C_1-C_0)^2}{A\cdot t(2C_1-C_2-C_0)}\ln\left(\frac{C_1-C_0}{C_2-C_1}\right)\ for\ t_2=2t_1\ and\ \frac{C_1-C_0}{C_2-C_1}>1 \qquad \text{(Eq. 3-3)}$$

Where *V* is the volume of the chamber (m^3), A is the soil surface area occupied by the flux chamber (m^2), C_o, C_1 and C_2 are the gas concentrations (mg/m^3) at times t_0, t_1, and t_2, and t is the time interval between t_0 and t_1, and t_1 and t_2 (d). In this case, the concentrations were measured three times during the same interval length t (i.e., every 10 min).

3.5.3 Data from the Vent System

The concentration values in ppm (raw data from laboratory) were converted to concentration in mg/m^3 using Eq. 3-1. The air velocity inside the pipe was measured using a hot wire anemometer. The air flow rate was calculated using Eq. 3-4.

$$Flow\ rate\ (m^3\,/\,d)=\pi r^2\cdot v \qquad \text{(Eq. 3-4)}$$

Where, r is the radius of the pipe (m) and v is the velocity inside the pipe (m/d). The mass flow of gas constituents was estimated as the product of the measured gas concentration (mg/m^3) and the measured flow rate.

CHAPTER 4.0

DESCRIPTION OF FIELD SITES

The selection criteria for the sites and septic tanks, the general characteristics of the sites chosen, a detailed description of each site septic system, the experimental approach for sampling at the septic tank, venting, and soil dispersal system and the preparation for field sampling are presented in this section.

4.1 Site and Septic Tank Selection

The Georgetown Divide Public Utility District (GDPUD) is the entity in charge of the wastewater management in the Auburn Lake Trails (ALT) development. The development is located in El Dorado County, next to highways 49 and 193, one mile from the town of Cool. ALT has development rights for the construction of 1,100 parcels; at present 999 lots have been developed (GDPUD, 2010). The GDPUD has a detailed inventory of the septic tanks located in Auburn Lake Trails development (38° 54’ 51.48”N, 120° 57’ 08.85”W) as well as records related to septic tank capacity, date of installation, pump out intervals, and maintenance. Based on the GDPUD information, a preliminary inspection of the septic tanks was conducted; seven tanks met the selection criteria for this study. An eighth tank, located in Davis, California, was also included in the study to perform 24-hour sampling events to capture the variability of GHG emissions throughout the day. The criteria used to select the eight septic tanks are described below:

- Site was readily accessible
- Tank access lids were easy to open/close
- Tanks were structurally sound, water-tight, and gas-tight
- The flow inside the vent system pipe was measurable
- The soil dispersal systems had appropriate land inclination for setting up sampling equipment

Following a series of preliminary gas emission measurements from all sites included in the study, several sites were selected for further evaluation based on accessibility and performance characteristics similar to a typical system, as discussed below.

4.2 General Site Characteristics

Sites 1 to 7 were located in the ALT development in Cool, CA, and Site 8 was located in Davis, CA. Gas samples from the septic tank liquid surface were taken at all the sites. Sites 1, 2, and 7 were selected for a more detailed study at the venting and soil dispersal systems and at Site 8, two 24 hour sampling events were performed.

All the systems were less than 15 years old, except for the septic tank at Site 8, which was built in the 1940s. All the septic systems were gravity flow systems, comprised of a septic tank and soil dispersal system, with no other advanced treatment. It should be noted that the onsite system at Site 8 also included a graywater system for the laundry water. All the septic tanks were double compartment concrete tanks and their capacity ranged between 1000 and 1250 gal. Sites 5, 6, and 7 were the only sites with effluent filters. It was noticed that the septic tank lids at Sites 1 and 7 did not seal as well as the other septic tanks. The first compartments of the septic tanks at Sites 2, 3, and 7 had well developed scum layers that ranged from 1 to 5". The first compartment of the septic tanks at Sites 1, 4, 5, 6, and 8 had only patchy or thin scum layers. A scum layer was never present in the second compartment of the septic tanks.

4.3 Description of the Individual Site Characteristics

A survey was given to each household, which included general questions such as number of occupants, water saving fixtures in the house, number of bathrooms, use of garbage grinder, and questions related to the septic systems such as pumping intervals and age of the system. More detailed information such as monthly water consumption, inspections, and maintenance records were provided by the GDPUD. The results of the survey and the information provided by the GDPUD are presented in Table 4-1.

Table 4-1. General Characteristics of the Septic Tanks in the Study Group.

	Septic tank number							
Characteristic	1	2	3	4	5	6	7	8
Location	ALT Development, Cool, CA							Davis, CA
Number of occupants	2	2	2	2	2	2	3	4
Water saving fixtures	LFS, LFT[a]	LFS, LFT	None	None	LFS, LFT	LFT	LFS, LFT	Greywater[b]
Number of bathrooms	2.5	3	3	2	2	2	4	4
Use of garbage grinder	Occasional	Rarely	Rarely	Rarely	Almost never	Almost never	Once/wk	No
Years since septic tank pumped	3	Never	Never	0.5	12	Never	3	>12
Date built	unknown	2005	1989	unknown	unknown	2002	unknown	1940s
Water consumption (L/capita·d)[c]	243	604	461	1345	411	84	170	180

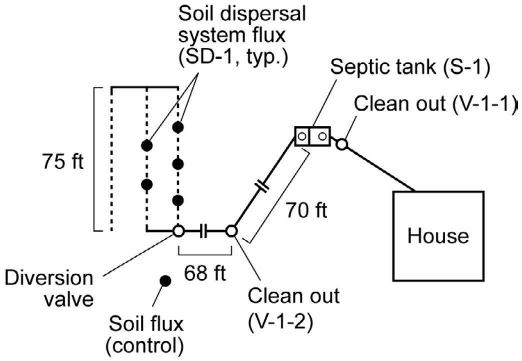
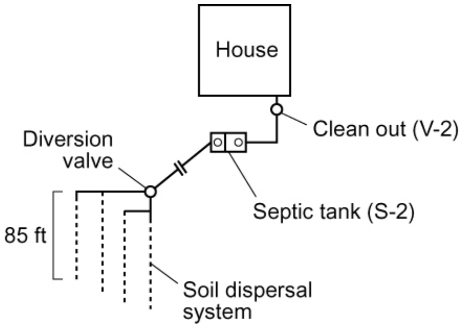
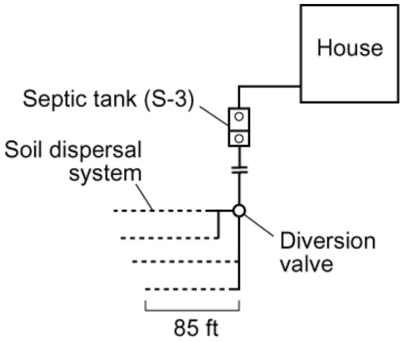
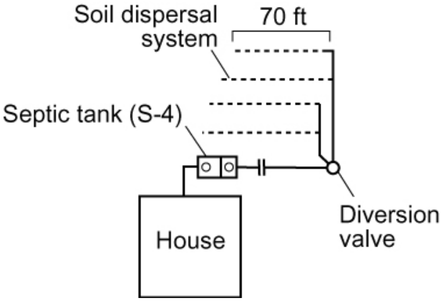
[a] LFS = low flow shower, LFT = low flow toilet.

[b] Laundry water diverted to greywater system.

[c] Average water usage based on winter season (November through February) 2008 - 2010.

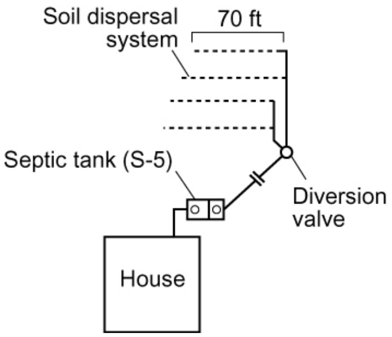
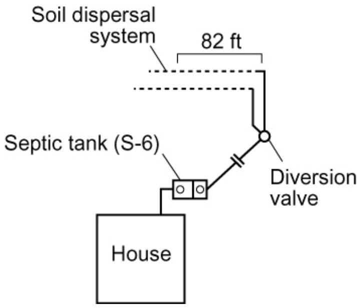
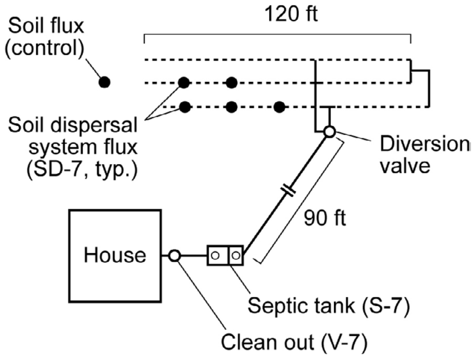
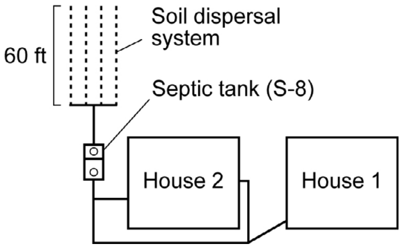
A plan view of the septic system including the septic tank, cleanout vent, and soil dispersal inserts along with a detailed description of the physical characteristics of the septic tanks such as the tank volume, capacity, and the inserts installed at each compartment to support the gas flux chambers during the sampling events are presented in Table 4-2.

Table 4-2. Physical Characteristics of the Eight Septic Tank Systems Used in the GHG Emissions Study. All Site Plans are not to Scale and Oriented with North Towards Top of Page.

Site	Site plan	System description
1		The septic tank, located in a shady area, has a capacity of 1200 gal. An insert was deployed in the first compartment of the septic tank to support the 6" flux chamber used to obtain the gas samples. It was not necessary to use an insert in the second compartment; the flux chamber was always deployed directly on the liquid surface.
2		The septic tank, located in a sunny area, has a capacity of 1200 gal. An insert was installed in the first compartment of the septic tank to hold a 6" flux chamber. It was not necessary to install an insert in the second compartment; the flux chamber was always deployed directly on the liquid surface.
3		The septic tank, located in the shade, has a capacity of 1250 gal. In the first compartment an insert to support a 6" flux chamber was installed. It should be noted that in the second compartment a 12" flux chamber was used to take the gas samples and it was deployed directly on the liquid surface.
4		The septic tank, located in a sunny area, has a capacity of 1000 gal. Inserts were not installed in this tank because it did not have a scum layer formation and therefore the 6 and 12" flux chambers used for the first and second compartment, respectively were always deployed directly on the liquid surface.

Continued on following page

Table 4-2. Continued from previous page.

Site	Site plan	System description
5		The septic tank, located in a sunny area, has a capacity of 1250 gal. Inserts to hold 12" flux chambers were installed in both compartments of the septic tank.
6		The septic tank, located in a partially shaded area, has a capacity of 1200 gal. Inserts to support 6" flux chambers were installed in both compartments.
7		The septic tank, located partially in the sun, has a capacity of 1200 gal. Inserts to support 6" flux chambers were installed in both compartments.
8		The septic tank, located in a partially shaded area, has a capacity of 1200 gal. Inserts to support 6" flux chambers were installed in both compartments of the septic tank. Site 8 was the only septic tank located in Davis, CA and it was selected to perform two 24-hr sampling events. A sanitary tee was not installed in the inlet.

4.4 Sampling Schedule

Gas flux measurements from all eight tanks were taken at various times over a four month period (September to December 2009) to attempt to capture the temperature effect on the GHG emissions. Due to external time constraints placed on this project, sampling could not be continued after December. The flux measurements and gas samples were taken in the septic tank, venting system and soil dispersal system. Each event included measurement of the gas flux and concentration of CH_4, CO_2 and N_2O. In addition, several water quality parameters (pH, dissolved solids, redox potential, COD, and aqueous methane concentration) were also measured in the inlet and outlet chambers of the septic tank. A summary of the sampling events, detailing the date, frequency, location and the parameters measured is provided in Table 4-3.

Table 4-3. Sampling Type, Location, and Frequency.

	Site[a,b]							
Date	1	2	3	4	5	6	7	8[c]
9/24	S’U,T	S,U,T	S,U,T	S,U,T	S,U,T	S,U,T	-	-
10/07	S,T	S,T	S,T	S,T	S,T	-	S,U,T	-
10/21	-	-	-	-	-	-	-	S,U,T
11/05	S,T,W	S,T,W	S,T,W	S,T,W	S,T,W	S,T,W	S,T,W	-
11/10	S,V,T	-	-	-	-	-	-	-
11/12	S,V,D,T, M	-	-	-	-	-	-	-
11/17	-	-	-	-	-	-	S,V,D,T, M	-
11/19	S,V,T,W, C,M	S,V,T,M	-	-	-		-	-
12/01	-	-	-	-	-	-	S,V,D,T, W,C,M	-
12/03	S,V,D,T, W,C,M	-	-	-	-	-	-	-
12/08	-	S,V,T,W, C,M	-	-	-	-	-	-
12/10	-	-	-	-	-	-	-	S,T,W, C,M
1/5	V, W							

[a] At each sampling event, three to six gas samples were taken from the septic tank (at each compartment), venting system (before and after the septic tank when possible), and soil dispersal system, identified as S,V and D, respectively. Each sample included measurement of the gas flux and concentration of CH_4, CO_2 and N_2O.
Sludge and scum thickness measurements are identified as U.
Water temperature measurements are identified as T.
Water quality measurements of pH, dissolved solids and redox potential are identified as W.
Dissolved methane measurements are identified as M.
COD measurements are identified as C.

[b] Sites 1 to 7 located in Cool, CA.

[c] Site located in Davis, CA.

Three of the septic tanks that appeared to have similar average gas emission rates (i.e., Sites 1, 2, and 7), and had accessible venting and soil dispersal systems were selected for additional gas flux measurements from the venting and soil dispersal system (see Table 4-2). This additional sampling was done with the intent of developing a mass balance on the overall methane emission rates from the system. The mass balance analysis, presented in Chap. 5, is based on data from Sites 1 and 7, where flux values from the septic tank, soil dispersal system, and vent system were obtained. The vent samples from Site 2 were used in developing the overall atmospheric emissions; however, because soil dispersal system flux was not determined at this site, it was not used in the mass balance analysis.

Flux chambers were designed and built to obtain flux measurements at the liquid surface and above the soil dispersal system. A special device was constructed to obtain flux measurements from the venting systems. The experimental apparatus and methods developed to sample from the three components (liquid surface, gas vent, and soil dispersal system) are described in Sections 3.1 and 3.2, respectively.

4.5 Preparation for Field Sampling

Preparations for each sampling day were made at least one day in advance. Before sampling, the use of personal protection equipment (PPE) was verified for all participants to avoid direct contact with the wastewater. PPE consisted of glasses, gloves and closed toe shoes. To assure a smooth and accurate sampling process, two to three people were required at each sampling event. Parameters measured in the field, comments and a full description of each site were recorded on sampling forms (see Appendix F) designed according to the component of the septic system (i.e., septic tank, soil dispersal system or vent system) analyzed.

Sampling vials (24 mL) were evacuated no later than one day prior to sampling. Two control vials with methane concentrations of 10 and 100 ppm, two controls with carbon dioxide concentrations of 1,000 and 10,000 ppm and two controls with nitrous oxide concentrations of 1.12 and 5.02 ppm were prepared in vacuumed vials to be taken to the field and analyzed along with the samples collected in the field.

CHAPTER 5.0

RESULTS AND DISCUSSION

The results from the field studies of the gas emissions from septic tanks are presented and discussed in this section. The specific topics include: 1) the GHG emission rates from septic systems, 2) mass balance analysis and 3) the sources of variability in gas emission rates. A summary of all data collected in the study is presented in Appendix H.

5.1 GHG Emission Rates from Septic Systems

Gas emissions from septic systems may be composed of gases produced in the septic tank, soil dispersal system, and drain piping. The items discussed below include: (a) specific gas emission rates from the septic tank measured with flux chambers, (b) composite gas emission rates estimated from sampling of the venting system, (c) gases present in septic tank liquid samples, (d) gas emission rates from the soil dispersal systems measured using flux chambers, and (e) comparison of methane emissions models

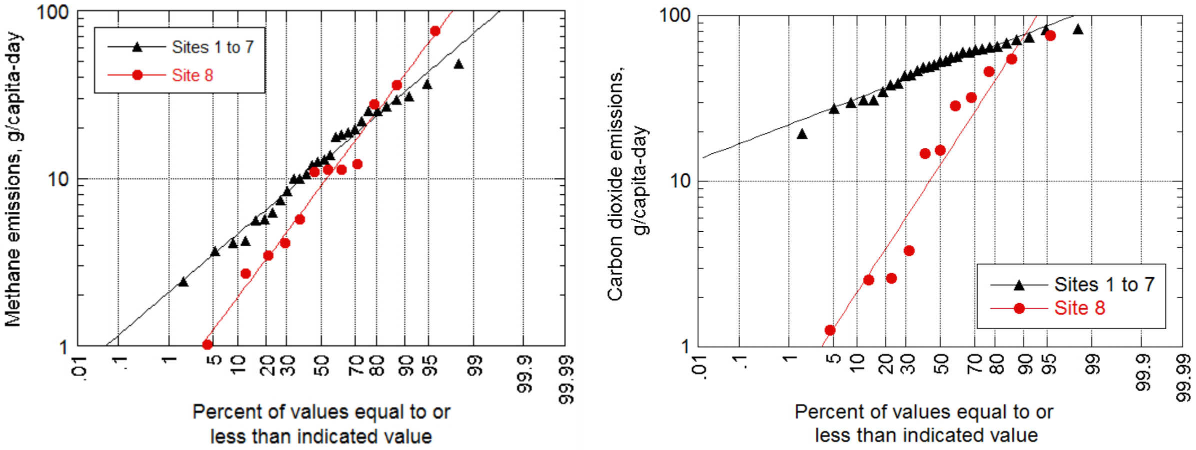
5.1.1 GHG Emission Rates from Septic Tanks as Measured Using Flux Chambers

The GHG emissions that were measured in this study include methane, carbon dioxide, and nitrous oxide. Eight septic tanks were sampled using 6 and 12” flux chambers. The gas bubble pattern in the septic tank is assumed to be random. Therefore, with a sufficient number of samples the statistical distribution of gas flux values should be identical, independent of whether the 6 or 12” flux chamber size was used.

While methane fluxes are attributed to anaerobic reactions occurring primarily in the sludge layer, carbon dioxide emissions result from anaerobic, facultative, and aerobic reactions. Similarly, nitrous oxide may be formed in the soil adsorption system as an intermediate product during nitrification and denitrification processes under low oxygen conditions, with high moisture and abundant nitrogen in the forms of urea, ammonia, or proteins (Bogner et al., 2007; U.S. EPA, 2009).

The flux of methane (geometric mean, M_g, and standard deviation, s_g) measured directly from individual septic tanks (excluding Site 4) was found to range from 6.3 ($s_g = 1.6$) to 17.9 ($s_g = 1.9$) g/capita·d. Site 4 was excluded from most of the analysis because it had been pumped out two months prior to the study and was found to be producing only small amounts of gas. Further discussion about the Site 4 septic tank and its GHG emission rates is presented in Section 5.3.3.

The geometric mean of methane flux values based on all flux chamber measurements (Sites 1 through 8, excluding Site 4) is approximately 11.0 ($s_g = 2.2$) g/capita·d. A plot of the data for Sites 1 through 7 (excluding Site 4) and Site 8 are plotted on Figure 5-1. Site 8 was plotted separately because it is in an area with a hard water supply and the values were collected over a 24-hr period. As shown on Figure 5-1, the slope of the curve fit for the Site 8 data is steeper than that for the rest of the sites. The steeper curve fit may be an indication of greater system instability as Site 8 was found to have excess solids beyond the amount recommended for tank cleaning. Another possibility is that the sampling from Sites 1 through 7 took place during the middle of the day, while the sampling from Site 8 took place over two all day sampling events.



(a) (b)

Figure 5-1. Emission Rate Values Measured Using Flux Chambers in Septic Tanks for (a) Methane from Sites 1 to 7, Excluding Site 4 ($R^2 = 0.96$), and from Site 8 ($R^2 = 0.98$) and (b) Carbon Dioxide at Sites 1 to 7, Excluding Site 4 ($R^2 = 0.94$) and from Site 8 ($R^2 = 0.84$).

As mentioned previously, carbon dioxide emission rates from septic tanks can be attributed to various metabolic processes taking place in the tank, including the anaerobic degradation of organic matter in the sludge layer and facultative activity occurring in aerobic and anoxic zones throughout the tank. The geometric mean of carbon dioxide flux values based on all flux chamber measurements (Sites 1 through 8, excluding Site 4) is 33.3 ($s_g = 2.7$) g/capita·d. The flux of carbon dioxide from individual tanks was found to range from a geometric mean of 30 ($s_g = 1.4$) to 59 ($s_g = 1.3$) g/capita·d. As shown on Figure 5-2, the carbon dioxide emission rates direct from septic tanks at Sites 1 through 7 (excluding Site 4) had less variability than the methane emission rates. It was observed that the carbon dioxide emission rates from Site 8 had a different distribution than the other septic tanks, and, therefore, it was plotted separately as shown on Figure 5-2.

The mean carbon dioxide flux from the septic tank at Site 8 was about a quarter of the value measured from the other sites. One possible explanation for the low carbon dioxide flux is attributed to a reaction with calcium carbonate likely present in high levels in the water supply at Site 8, discussed further in Section 5.3.1. By comparison, Sites 1 through 7 had a relatively soft water supply.

Septic tanks were not found to be a significant source of nitrous oxide. Nitrous oxide emission rates from septic tanks were found to be negligible using the flux chambers when sampling directly from septic tanks. The measured nitrous oxide concentrations were around 0.31 ppm, which corresponds to ambient concentrations. When considering all sites, the flux of nitrous oxide ranged from 0 to 0.03 g/capita·d, with a geometric mean of 0.005 ($s_g = 4.35$) g/capita·d.

5.1.2 GHG Emission Rates Measured Using the Vent Method

It was found that the air movement in the household drainage system originates in the soil dispersal system and flows back through the septic tank headspace and out of the building vent. Based on this finding, it was proposed that the gas emissions from septic systems could be assessed by sampling from the vented gases in the household drainage system because the gases measured in the vent system integrate the emission rates from both the septic tank and the soil dispersal system and, therefore, may be a good representation of the overall emissions of a septic tank system.

Average emission rates of methane, carbon dioxide, and nitrous oxide, measured using the vent method (i.e., combined emission rate from septic tank and soil dispersal system), were 10.7 ($s_g = 1.65$), 335 ($s_g = 2.1$), and 0.2 ($s_g = 3.6$) g/capita·d, respectively. There was general agreement between the flux chamber and vent method for methane, indicating that the primary source of methane gas was the septic tank itself (see Figure 5-2). In contrast, the carbon dioxide emission rates using the vent method greatly exceeded the amount produced in the septic tank, indicating that there is significant carbon dioxide production in the soil dispersal system. A detailed comparison of the vent sampling and flux chamber methods is presented in Section 5.2.1.

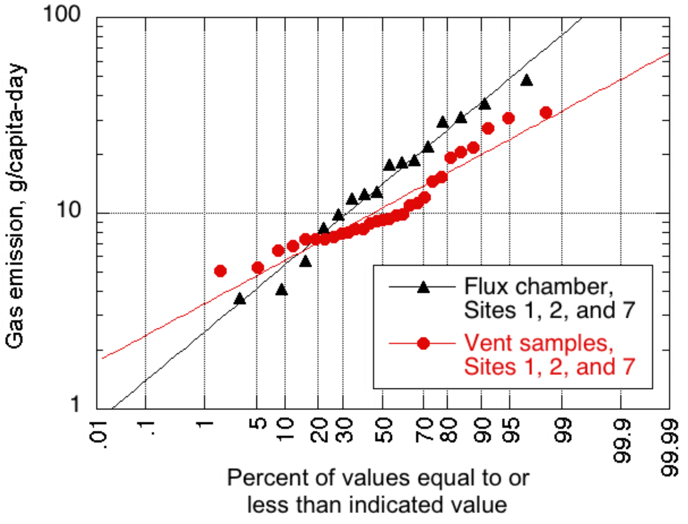


Figure 5-2. Comparison of Methane Emission Rates Using the Flux Chamber and Vent Method for Sites 1, 2, and 7.

5.1.3 Gas Concentrations in Septic Tank Liquid Samples

Gases were extracted from septic tank liquid samples to determine the amount of dissolved and entrained gases present. Nitrous oxide was not present in the liquid samples above the detection limit. The theoretical solubility values for methane, carbon dioxide and nitrous oxide in mg/L are 0.0004, 0.66 and 0.34, respectively. The methane and carbon dioxide concentrations in the liquid were measured at Sites 1, 2, and 7. The average carbon dioxide concentrations in the septic tank first and second compartment were 15.6 and 6.3 mg/L, respectively, and for methane were 4.0 and 1.3 mg/L, respectively. The measured concentrations for carbon dioxide and methane in the septic tank liquid samples at these sites were high in relation to the theoretical solubility limits. One possible explanation for the high liquid phase concentrations of these gases is that they are present as small bubbles that do not effervesce readily due to their small size.

Based on these measurements, it is estimated that the methane discharged with the effluent from the septic tank varies from 0-1.4 g/capita·d, or 0-11% of the total methane generated (flux chamber emission rate value plus gases discharged with liquid). The liquid methane values are lower than those given by Sasse (1998). Sasse (1998) suggested that dissolved methane generated in a septic tank could range from 25-50%. While Sasse (1998) does not go into detail on the origins of the percentages for dissolved methane, all the values used in the Sasse (1998) model were based on statistics from septic operated at higher temperatures and loading rates. As shown on Figure 5-3, there was not a clear correlation between the gas emission flux and the effluent aqueous methane.

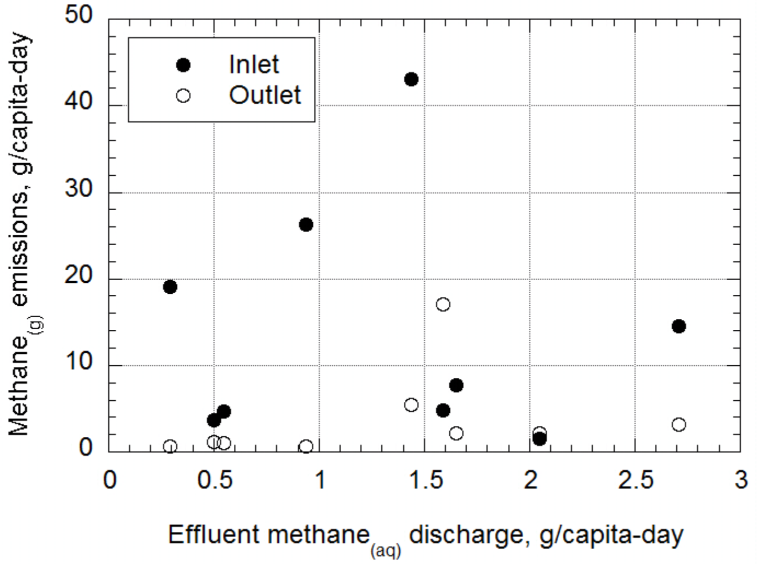
At Site 8, the dissolved methane concentrations in the first and second compartment were 2.6 and 1.9 mg/L and for carbon dioxide 12.1 and 10.0 mg/L, respectively. Compared to the other sites, these dissolved methane concentrations were low in the first compartment and similar in the second compartment. The carbon dioxide concentrations had a low value in the first compartment compared to the other sites and a high value in the second compartment. Dissolved nitrous oxide was not detected in the effluent liquid at Site 8.

5.1.4 Gas Emission Rates from the Soil Dispersal System

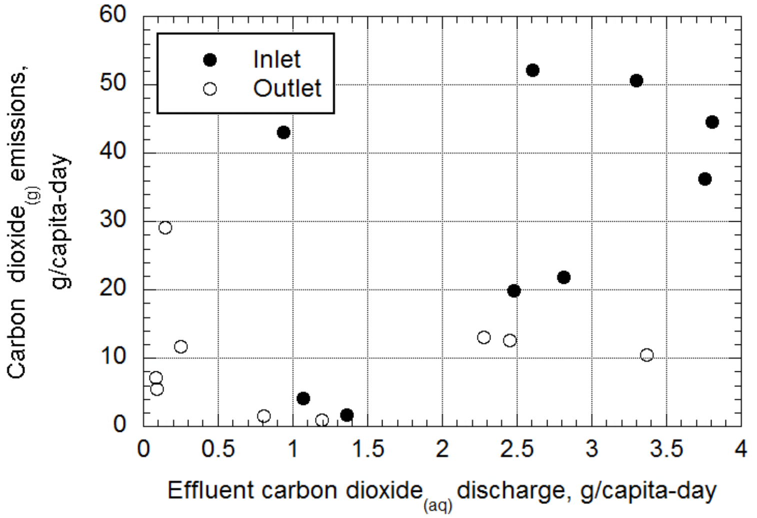
Flux chambers placed directly above the effluent pipes in the soil dispersal system were used to estimate the GHG emissions to the atmosphere resulting from diffusion of gases through the soil. However, it was found that the GHG concentrations obtained from flux chambers located above the soil dispersal system were similar to concentrations in ambient atmosphere samples. As discussed previously, the flow of air from the soil dispersal system back through the building vent system is a likely explanation for the lack of soil-based gas emissions. It is proposed that the semi-constant negative pressure in the soil dispersal system acts to pull off-gases from metabolic processes in the soil through the effluent dispersal pipes and building vents. For example, during the first sampling event at Site 1, gas flux was found to be zero above the soil dispersal system, however, a methane emission rate of 0.8 g/capita·d was detected for the control sample. During the next sampling event at Site 1, only one of the six samples from above the soil dispersal system had measurable emission rates of carbon dioxide and nitrous oxide, however both values were similar to the control. For Site 7, carbon dioxide and nitrous oxide emission rates were measured at similar concentrations in the control and in two of the samples from above the soil dispersal system.

5.2 Mass Balance Analysis

A mass balance analysis was used to determine and compare gas emission rates from the emission sources (septic tank and soil dispersal system) identified in the previous section. The analysis presented below includes mass balances on (a) the septic tank only for a comparison of the flux chamber and vent sampling methods, (b) the septic system to determine the overall atmospheric emissions of GHG, and (c) the soil dispersal system to assess the fate of carbon. The percentage of methane and carbon dioxide in the measured emission rates is also presented in this section.



(a)



(b)

Figure 5-3. Comparison of Gas Emission Rates from Septic Tanks and from Dissolved Gases in the Septic Tank Effluent: (a) Methane and (b) Carbon Dioxide.

5.2.1 Mass Balance on the Septic Tank

A mass balance around the septic tank can be made to compare the results of the gas emission rates measured with the flux chamber and with the vent method for Site 1. Only Site 1 is used for this analysis because cleanout ports that could be used for gas sampling were located both before and after the septic tank, allowing for differentiation of the tank and soil system emission rates. As shown in Figure 5-4, the gases coming from the soil dispersal system were measured at the cleanout port located in the pipe after the septic tank (vent sample point V-1-2) and the composite gases leaving the tank (soil dispersal system + septic tank) were those measured at the cleanout located before the septic tank (Vent sample point V-1-1). The net emission from the septic tank is obtained by subtracting the gas emission rates value measured at V-1-2 from that at V-1-1. The results from the mass balance, in g/capita·d for methane, carbon dioxide and nitrous oxide are 8.4, 423.4, and 0.29, respectively. These can be compared with values of 17.9, 54.4, and zero as measured using the flux chamber in the septic tank.

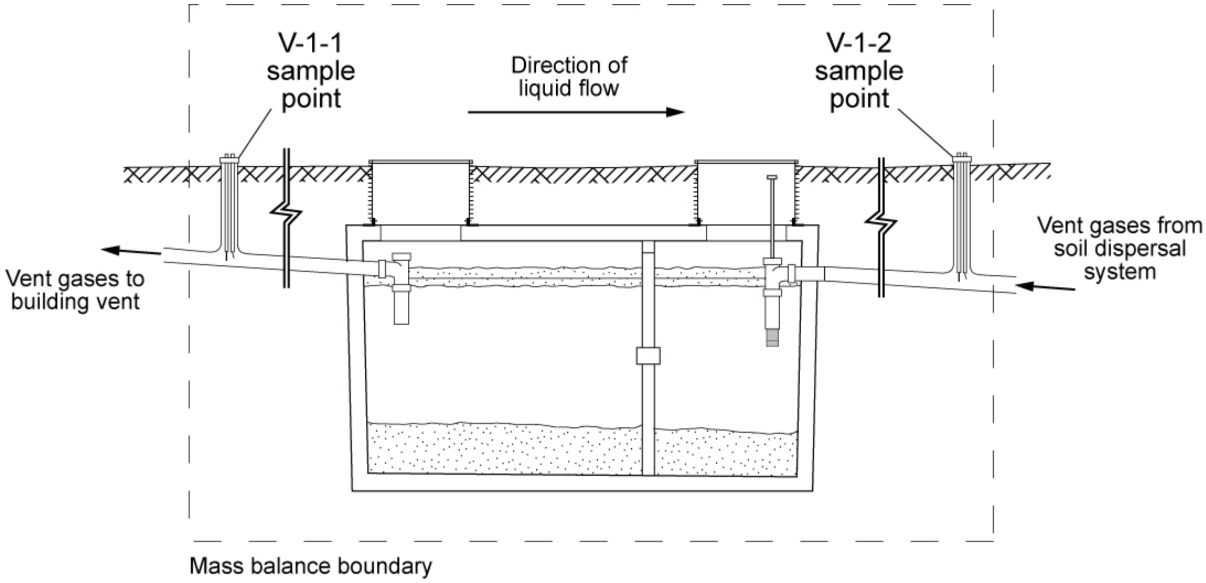


Figure 5-4. Definition Sketch for Mass Balance for Gases Moving Through the Septic Tank.

As presented in Table 5-1, the mass balance value for methane using the values measured with the flux chamber was higher than that measured with the vent method. Potential reasons for the positive bias in the flux chamber measurements compared to the vent measurements are (a) the flux chamber method draws samples from near inlet where wastewater enters the tank and possibly results in increased microbial activity, (b) wastewater discharges into the tank cause some mixing in the tank that dislodges gas bubbles from the sludge layer near the inlet, (c) the gas velocity measured in the vent system using the anemometer was lower than the actual mean velocity, and (d) insufficient samples were obtained to characterize the distribution. However, further work is necessary to determine which of these reasons (if any) is the actual cause of the discrepancy. It should be noted that if (a) or (b) is occurring, the value measured using the vent system may be more representative of the actual emission rates, whereas an incorrect velocity measurement (c) would suggest that the flux chamber measurements may be more accurate. Additional sampling should be conducted to eliminate item (d) as a possibility.

Note that methane was not detected above the ambient background in the gas samples taken at sample point V-1-2. However, a relatively high flux of carbon dioxide and nitrous oxide was determined at sample point V-1-2, resulting from the aerobic degradation of septic tank effluent in the soil. The measured results for all of the GHG's are shown in Table 5-1.

Table 5-1. Comparison between Mass Balance Values and Actual Measurements for Site 1.

	Gas emission rate, g/capita·d					
	CH_4		CO_2		N_2O	
Site	MB[a]	FC[b]	MB	FC	MB	FC
1	8.4	17.9	423.4	54.4	0.29	0.0

[a] MB = Result from the mass balance based on subtracting the emission rates measured at V-1-2 from those measured at V-1-1.

[b] FC = Value measured with the flux chamber.

A comparison of the methane emission rates obtained with the flux chamber and the vent method is shown on Figure 5-5. The vent data have less variability than the flux chamber data, as indicated by the shallower slope of the trend line fit through the data. The reduced variability from the vent system data is likely to be the result of the composite nature of the vent sample (flux values averaged over the whole system), compared to the instantaneous measurement obtained with the flux chambers (flux value extrapolated based on emission rate measured for a small area).

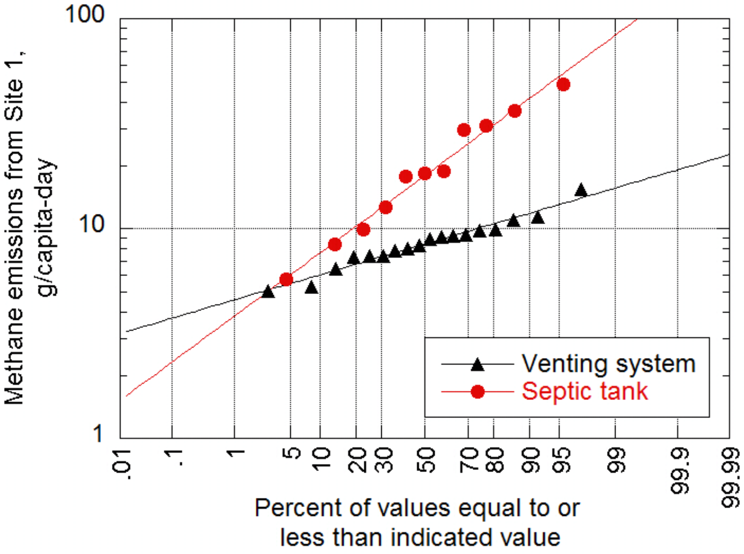


Figure 5-5. Comparison of Methane Emission Rates from the Venting System (R^2 =0.96) and the Septic Tank at Site 1 (R^2 =0.96).

5.2.2 Mass Balance on the Septic System

A mass balance on the septic system was performed to determine the overall atmospheric emissions from the system. As shown in Figure5-6 the emissions from the entire system consist of atmospheric emissions from the building vent to the air, atmospheric emissions from the soil dispersal system to the air, and gases discharged with the effluent to ground water. It should be noted that in this approach it is assumed that there are no gases escaping elsewhere in the system. Sites 1 and 7 were used for this analysis because measurements were made from both the vent and above the leach fields. In all cases the discharge of gases to the groundwater was assumed to be negligible.

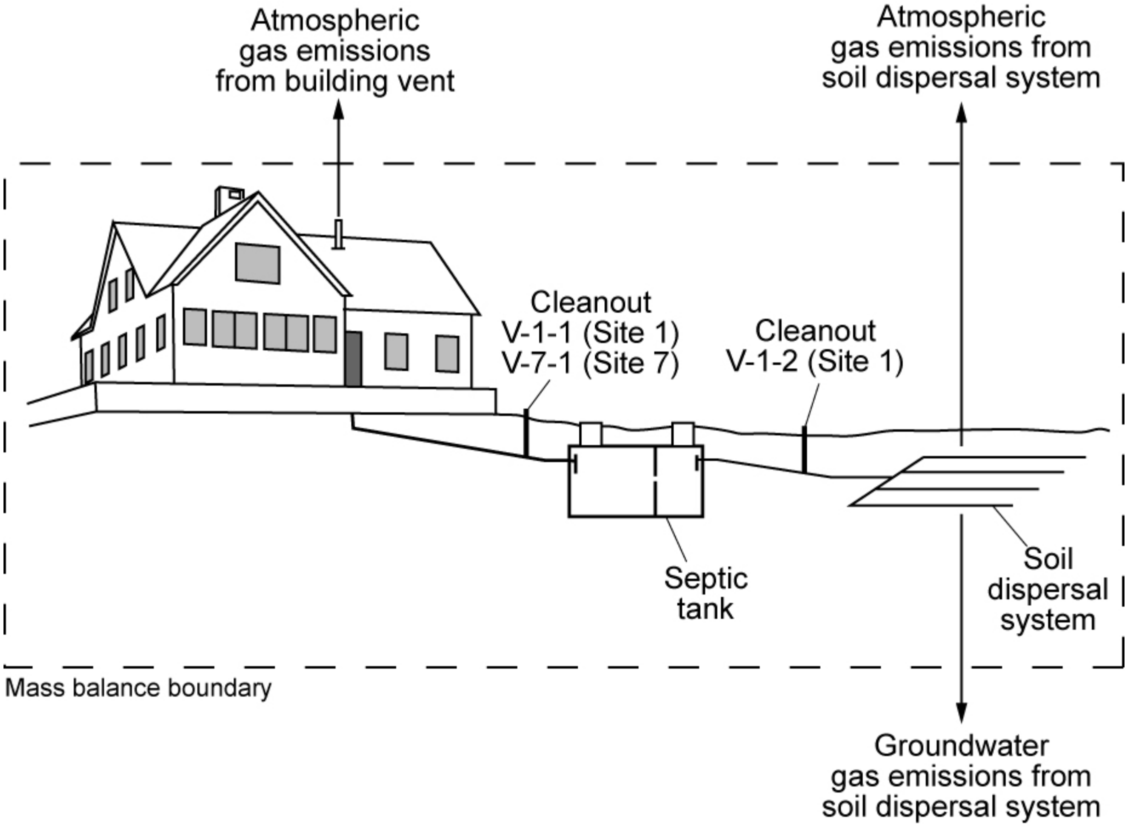


Figure 5-6. Definition Sketch for Mass Balance for Total Gas Emission Rate from the Septic System.

As discussed in Section 5.1.4, the gas emission rates from the soil dispersal system were not significantly different from the experimental control, possibly because the gases are being withdrawn through the ventilation system. Therefore, the overall atmospheric emissions from the septic system can be estimated entirely from the samples taken from the vent system located before the septic tank.

Based on the measurements at V-1-1 the overall geometric mean of the emission rates at Site 1 for methane, carbon dioxide, and nitrous oxide are 8.4, 527.0, and 0.37 g/capita·d, respectively. For Site 7, the emission rate values for methane, carbon dioxide, and nitrous oxide were 13.4, 93.0, and 0.04 g/capita·d, respectively. Note that these values are unadjusted for potential errors in the gas velocity measurement, as noted above. A summary of the mass balance results is presented in Table 5-2.

Table 5-2. Results of the Mass Balance Analysis on the Emission Rates from Septic Systems. Note: All of the Atmospheric Gas Emission Rates from These Two Systems were from the Building Vent.

	Gas emission rate, g/capita·day[a]		
Site	CH_4	CO_2	N_2O
1	8.4	527.0	0.37
7	13.4	93.5	0.04
Average	11.2	310.2	0.20

[a] The reported values correspond to averages from all the vent measurements at each site and can be found in the Appendix H.

5.2.3 Mass Balance in the Soil Dispersal System

To determine the fate of carbon present in the septic tank effluent, a mass balance analysis in the soil dispersal system was performed. The input of carbon to the system can be estimated from the COD of the septic tank effluent. The carbon dioxide equivalent of COD was determined using a stoichiometric approach where domestic wastewater is represented by the compound $C_{10}H_{19}O_3N$ (Metcalf and Eddy, 2003). The calculation of CO_2 production from COD oxidation is shown in Appendix I.

As discussed previously, direct atmospheric emissions of GHGs from the soil dispersal were determined to be insignificant. The discharge of carbon to the groundwater is assumed to be insignificant. The amount of carbon leaving the soil dispersal system can therefore be estimated by the vent samples obtained from V-1-2 as shown in Figure 5-7. Based on the system carbon balance, the carbon dioxide equivalent of the COD should be approximately equal to the CO_2 leaving the soil dispersal system through the ventilation system.

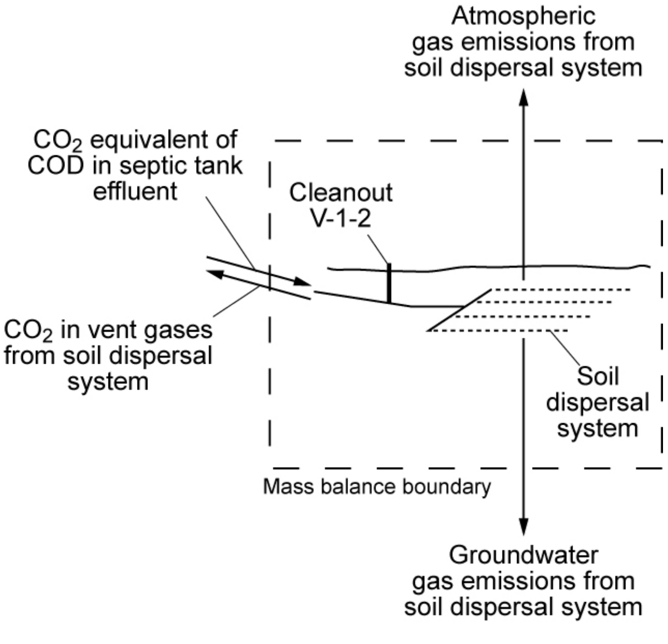


Figure 5-7. Mass Balance on the Soil Dispersal System.

The septic tank effluent CO_2 equivalent of the COD is calculated to range from 45-133 g/capita·d, depending on flowrate (see Appendix I), and the average CO_2 emission rates measured at V-1-2 is 104 g/capita·d. The approximate agreement between these values is an indication that the carbon that enters the soil dispersal system is mostly oxidized in the soil to CO_2 and this CO_2 flows back through the drainage pipes and escapes to the atmosphere through the building vent.

5.2.4 Percentage of Methane and Carbon Dioxide in the Overall Emissions

The majority of the gases expected from anaerobic degradation are methane and carbon dioxide. Therefore, the percent of each gas per sample was calculated assuming these were the only two gases present. It was found that at Sites 1 to 7 the average methane content was approximately 35% (by volume) and 65% carbon dioxide (see Figure 5-8). The high carbon dioxide percentage may indicate that there are other microbial processes occurring in the septic tank, such as aerobic or facultative bacterial activity, in addition to methanogenesis. The large amount of air moving through the venting system and headspace of the tank removes methane and carbon dioxide gases and supplies oxygen to the liquid or scum surface, potentially creating an environment for aerobic degradation to take place. Gas emission rates from Site 8 had a higher average methane content, around 65% and therefore 35% for carbon dioxide (see Figure 5-8), which agrees with the results of Winneberger (1984), where a gas mixture composition of approximately 70% methane in a septic tank was reported.

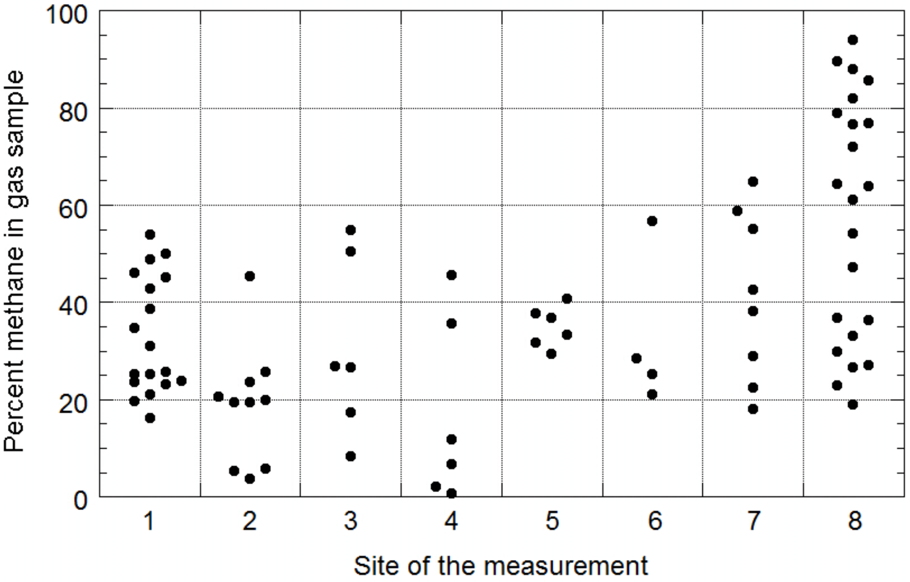


Figure 5-8. Percent Methane in the Gas Mixture at All the Sites.

The mixture that would be expected typically in an anaerobic digester is 65% methane and 35% carbon dioxide (Metcalf and Eddy, 2001). Site 8 has a similar gas mixture composition to the anaerobic digester, which may be an indication that this tank had a higher anaerobic activity than the other tanks. Another reason for the lower average carbon dioxide emission rate at Site 8 is related to the possible reaction of carbon dioxide with the high calcium carbonate content of the water supply, which is discussed in Section 5.3.1.

5.3 Sources of Variability in Gas Emissions

A number of factors contributed to the wide variability in the gas emission measurements recorded for the septic systems included in this study. The influence of factors such as water hardness, presence of scum layer, pumping intervals, turnover events, presence of invertebrates, temperature, and the septic tank effluent filter are discussed in this section.

5.3.1 Water Hardness Influence on Carbon Dioxide Emissions

As mentioned previously, the water supply for the Auburn Lakes Trails (ALT) development, encompassing Sites 1 through 7, originates in the Sierra and flows into the Strumpy Meadows Reservoir; it has an average hardness content of 9 mg/L as $CaCO_3$ (GDPUD, 2009) which indicates a soft water supply. In contrast, the water that serves the tank located in Davis is pumped out from a groundwater well and has an average hardness of 212 mg/L as $CaCO_3$ (CDPW, 2009) indicating a hard water supply.

A comparison of the carbon dioxide emission rates data between the sites located in ALT and the tank for Site 8 (Figure 5-2) indicates different distributions. It is hypothesized that the hardness content of the water supply in each area may be a reason for this differing behavior. In addition to the difference in source water, Site 8 had other distinguishing characteristics that potentially impacted emissions. Unique aspects at Site 8 include the diversion of laundry water to a gray water system, a higher number of occupants per tank volume, and the vegetarian diet of the house occupants. It is conceivable that these aspects may also influence the overall anaerobic and facultative processes occurring in the tank and hence the carbon dioxide emission rates.

5.3.2 Influence of Scum Layer on Gas Emissions

Two different groups of sites were compared to determine the influence of the scum layer in the overall emissions from the septic tank. The first group was composed of the tanks from Sites 2, 3, and 7 that share as a common characteristic a thick scum layer varying from 3 to 5 inch in depth, with similar appearance, black color, humus like texture and usually covered the liquid surface of the septic tank. The septic tanks at Sites 1, 5, and 6 formed the second group; these tanks were characterized by patchy, light scum (less than 1"), with a light brownish color. As shown on Figure 5-9, the average methane and carbon dioxide emission rates from the sites that have a thick scum layer are similar to the sites without scum and the slopes are also similar. The data from the septic tank at Site 8 (light scum, hard water) was plotted separately for comparison.

5.3.3 Emissions from Recently Cleaned Tank

The septic tank located at Site 4 was not a typical septic tank. It did not have any scum formation; the sludge was less than 14" in depth, with a light brown coloration and a particular pine odor was emitted when the tank lids were opened. The tank was last pumped out in late July of 2009 (measurements took place during September 2009). The methane and carbon dioxide gas emission rates from the tank at Site 4 in g/capita·d, averaged 0.2 and 3.2, respectively. Nitrous oxide emission rates were negligible. From the results of the overall GHG emission rate and the characteristics of the tank discussed above, it can be assumed that methanogenesis was not occurring in this tank, which is consistent with results reported by Weibel et al. (1955) for recently pumped septic tanks, which had a lag phase in the gas production.

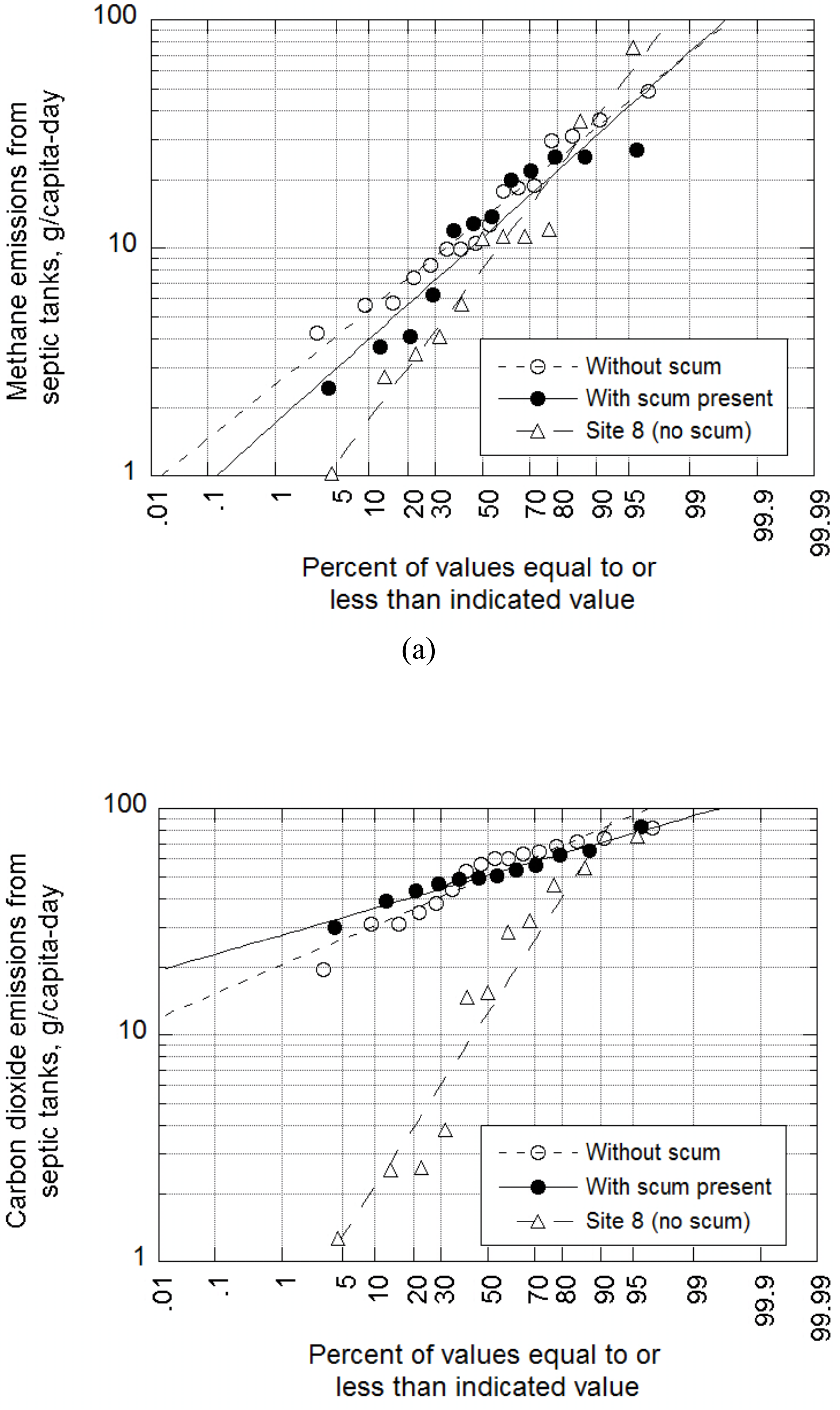


Figure 5-9. Gas Emission Rates Results Grouped Based on Presence of Scum: (a) Methane and (b) Carbon Dioxide.

5.3.4 Influence of Turnover Event on Septic Tank Gas Emissions

Several turnover episodes were observed in the septic tank at Site 1 during the course of the study. As shown in Figure 5-10, during the turnover event, a large number of bubbles and sludge came to the surface, causing the tank contents to mix with subsequent gas release to the atmosphere. A gas sample taken using the flux chamber before the turnover event had a flux of methane of 43 g/capita·d while the methane flux after the turnover event was 18 g/capita·d. The reduction in the emission rates indicates that the tank released the methane gas trapped in the sludge during the turnover events. It was surprising to observe these episodes during fall and early winter in light of the observations of Winneberger (1984) and D’Amato et al. (2008) that these events (will) happen more frequently during the spring and summer months when anaerobic activity increases due to the rise of temperature..

Figure 5-10. Views of Tank at Site 1 (a) Just Before and (b) During a Turnover Event.

5.3.5 Variability in Daily GHG Emissions

High variability was observed in the methane emission rates from tank to tank and from sample to sample for a given tank, highlighting the danger of generalizing on the basis of single measurements or single sites. A good example is Site 8, where the 24-hour sampling events took place. As shown in Figure 5-11, two particular periods with comparably high methane emission rates were observed, one at 7:00 am and another at 11:00 pm.

These high emission periods correlated with activities that were taking place in the house at the time of sampling, bathing during the 7:00 am sample and manual dishwashing at the 11:00 pm sample, indicating that the high methane emission rate values may be related to the water usage in the house. It is proposed that the sludge at the bottom of the tank may be disturbed when water is discharged to the septic tank, resulting in the release of gas bubbles that have accumulated in the sludge layer. The flux of carbon dioxide does not appear to follow the same trend as methane, which may be related to the reactions of carbon dioxide in the water. The cause of the low emission rate of carbon dioxide on the 12/10/09 sample event has not been determined.

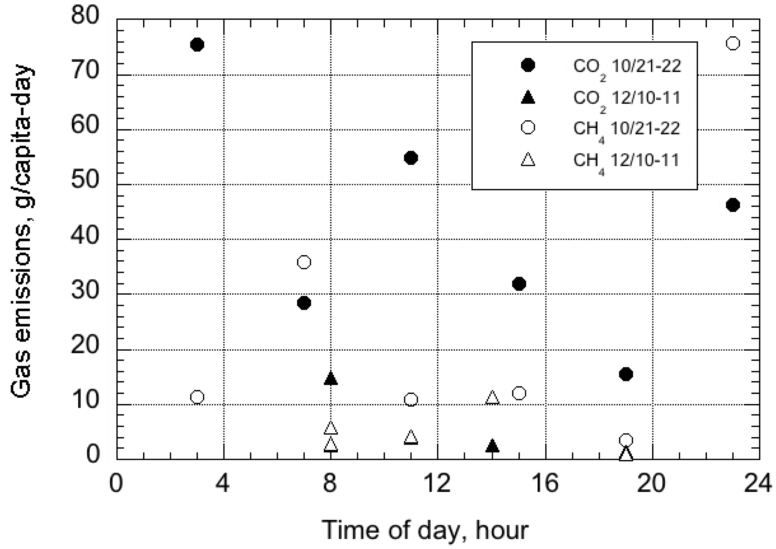


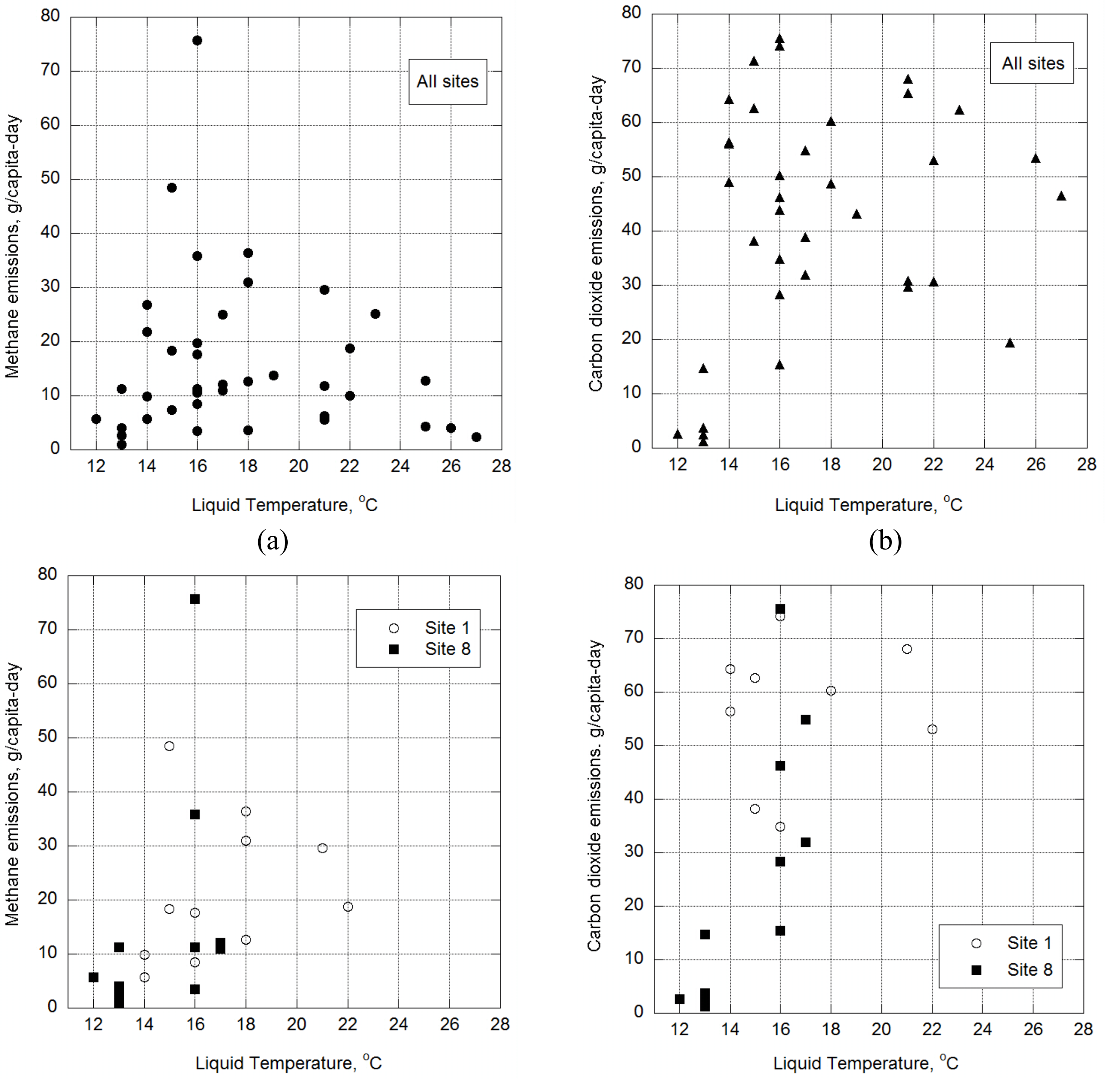
Figure 5-11. Emission Rates from Site 8 During the Two 24-Hour Sampling Events for Methane and Carbon Dioxide.

5.3.6 Relation between Invertebrates and Scum Layer

Sites 2, 3 and 7 had a thick scum layer and the presence of invertebrates such as red worms and small flies. It was confirmed that a thick scum layer with dark brown to black coloration and with the appearance of "crumbly earth" or humus were populated by earthworms as reported by Winneberger (1984). It was observed at the time that small flies and its larva were also living on the upper layers of the scum, as previously reported by Dale (1982). However, a larger number of organisms were not found to correspond to a thicker layer of scum as was observed by Dale (1982). Small black larvae were observed at Sites 6 and 8 in where the scum layer was thin (less than 3 cm).

5.3.7 Temperature Influence on Gas Emissions

The average liquid temperature inside the tanks ranged from 12-27ºC during the four months of sampling. Kinnicutt et al. (1910) and Winneberger (1986) reported a reduction in gas emissions during cold months, however, no correlation between the average liquid temperature inside the septic tanks and the overall methane and carbon dioxide emissions was observed in this study (Figure 5-12). The sites with the largest number of measurements (Sites 1 and 8) were also plotted separately to identify a possible trend with temperature; none is apparent (Figure 5-12 c and d). While it is possible that the sampling duration and range of temperatures in this study were insufficient to characterize the seasonal temperature variation, the more likely reason is that factors other than temperature play a more important role in determining the measured emission rates at any given time/location (for example, the diurnal measurements presented on Figure 5-12).



(a)
(b)
(c)
(d)

Figure 5-12. Comparison of the Average Gas Emission Rates and the Liquid Temperature: (a) Methane and (b) Carbon Dioxide Emission Rates at Sites 1 to 7, (c) Methane and (d) and Carbon Dioxide Emission Rates at Sites 1 and 8.

5.3.8 Influence of the Effluent Filter in the Venting System

The influence of the effluent filter on the air flow from the septic tank through the vent system was evaluated at Sites 1 and 7. It was found that gas flow rates in the passive house venting systems ranged from 150 to 400 m^3/d when an effluent filter was not present. Effluent filters reduced the air flow through the vent system to a range of 10 to 70 m^3/d, depending on the type of filter (see Figure 5-13). Thus, it was found that effluent filters may obstruct the natural flow of air through the tank headspace. Flow of air through the tank headspace is important for the evacuation of methane (an explosive gas) and odor causing compounds. Thus, improved designs for effluent filters may be needed to prevent the accumulation of these gases in the tank headspace, particularly under calm weather conditions when flow in the vent systems is reduced.

(a)

(b)

Figure 5-13. Views of the Effluent Filters: (a) Filter in Effluent Tee and (b) Comparison of Two Types of Filters. Internal Elements of the Filter are Removed for Viewing.

CHAPTER 6.0

IMPLICATION OF RESULTS

An important part of this research is to provide field data that can be used as a basis for comparison with previous studies and for calibration of GHG emission inventory models. In the following discussion, the emissions findings from this study are: 1) compared to values found in the literature review and model values and 2) evaluated in terms of their global warming potential.

6.1 Comparison of Gas Emissions to Literature Values and Models

A summary of the literature emission values and those measured using the flux chamber is presented in Table 6-1. The average methane emission rate obtained using flux chambers in the septic tanks were in general agreement with the estimates of methane emission rates based on the COD loading and Kinnicutt et al. (1910) models. However, these averages are somewhat lower than the estimates from Winneberger (1984) and Sasse (1998) and much lower than the IPCC (2007) model for methane emission rate in septic tanks.

Table 6-1. Summary of Methane Emission Rates, Including this Study.

Method	Year	Methane estimate ($g\ CH_4$/capita·d)
Kinnicutt et al.	1910	10.1[a]
Winneberger	1984	14 to 18[a]
COD loading	2010	11[b]
IPCC	2007	25.5[c]
Sasse	1998	18[d]
This study	2010	11.0 ($s_g = 2.50$)[a,e]

[a] Measured value from community septic tanks.
[b] Calculated value assuming that 40% of solids are removed as septage (see Appendix B).
[c] Calculated value assuming that half of the influent BOD is converted anaerobically (see Appendix C).
[d] Calculated value assuming 25% CH_4 dissolved (see Appendix D).
[e] Geometric mean and standard deviation as determined using flux chamber method, this study.

One reason for the difference between the measurements presented here and those determined from the IPCC (2007) model is that the IPCC (2007) model assumes that half of the influent BOD to the septic tank is converted anaerobically. Further, the fate of organic matter present in septage and septic tank effluent is not accounted for clearly. It is likely that the measurements made by Winneberger (1984) are high because not enough samples were obtained to establish a statistical distribution. The values used in the Sasse (1998) model were based on statistics from septic tanks located in developing countries, which may operate at higher temperatures and loading rates, resulting in higher methane emission rates.

It is important to note that the U.S. EPA (2010) GHG emissions model for septic systems uses an approach similar to the IPCC (2007) model; using a methane correction factor (MCF) of 0.5 (see Section 2.5.2). However, this value does not specifically account for the fate of the sludge when the tank is cleaned out or for effluent BOD oxidation in the soil dispersal system. Based on the mean methane emission value measured in this study (11 g CH_4/capita·d), an MCF value of about 0.22 would be applicable for the systems evaluated in this research project.

6.2 CO_2 Equivalent of Gas Emissions Values

The septic tank emission rates for methane and nitrous oxide have been converted to CO_2-equivalent (CO_2e) emissions using the global warming potential for a 100 year horizon based on the IPCC (1996) values. The CO_2e is calculated by multiplying the measured emission rates by the GWP, as summarized in Table 6-2.

Table 6-2. Summary of Emission Rates as CO_2e from the Septic Tank and Vent Average Measurements.

	Geometric mean emission rate value (g/capita·d)			Carbon dioxide equivalent emissions (tonne CO_2e/capita·year)	
Compound	Septic tank	Septic system[b]	GWP[a]	Septic tank	Septic system[b]
Methane	11.0	10.7	21	0.084	0.082
Nitrous oxide	0.005	0.20	310	0.00057	0.023
Carbon dioxide	33.3	335	1	0.012	0.12
Total GHG emissions				0.096	0.23
Total anthropogenic emissions[c]				0.085	0.10

[a] GWP for a 100 year horizon IPCC (1996).

[b] As determined from vent system sampling.

[c] Biogenic carbon dioxide is not included in GHG inventories (U.S. EPA, 2009).

As shown in Table 6-2, methane generation from the septic tank is the primary source of anthropogenic GHG emissions. The CO_2e GHG emission rates from septic tank systems determined using either the flux chamber or mass balance methods are relatively low compared to those for a citizen of an industrialized country (about 23 tonne CO_2e/capita·year; U.S. EPA, 2010). Using the total emission values reported in U.S. EPA (2010), the per capita GHG emissions associated with wastewater treatment are 0.13 and 0.92% for centralized and decentralized (i.e., systems with onsite septic tanks), respectively. However, using the adjusted emission values as determined in this study, the GHG emissions associated with septic tank type systems are about 0.47% of the average per capita GHG emissions, resulting in an estimated total emission of about 6.5 Tg CO_2e/year from septic tank systems. It should be noted that these GHG inventories do not account for the embodied GHG emissions associated with construction or maintenance of infrastructure, process chemical and energy inputs, or downstream environmental impacts. Thus, this type of GHG emissions comparison is limited in that it is based solely on fugitive methane and nitrous oxide emissions.

CHAPTER 7.0

FINDINGS AND RECOMMENDATIONS

The major findings of this research study, other findings, and recommendations for future studies are presented in this section.

7.1 Major Findings

The principal findings from this research are:

- The geometric mean of the total emission rates for methane, carbon dioxide, and nitrous oxide based on samples from the vent system were 10.7 ($s_g = 1.65$), 335 ($s_g = 2.13$), and 0.20 ($s_g = 3.62$) g/capita·d, respectively.
- The CO_2e of the methane emission rate to the atmosphere, as determined from the vent system data in this study, is about 0.10 tonne CO_2e/capita·yr. Based on the current estimated per capita CO_2e emission rate for the United States (i.e., 23 tonne CO_2e/capita·yr; U.S. EPA, 2010), the septic tank system accounts for about 0.5% of the total per capita emission.
- The septic tank methane flux values determined by the flux chamber method were found to have a log-normal distribution, with a geometric mean (M_g) of 11.0 g/capita·d and geometric standard deviation (s_g) of 2.50. Similarly, the values of M_g for carbon dioxide and nitrous oxide were 33.3 ($s_g = 2.73$) and 0.005 ($s_g = 4.35$) g/capita·d, respectively.

7.2 Other Findings

Other findings from this research are:

- There was general agreement for methane gas emission rates determined with theoretical models and measured with the flux chamber and vent methods.
- There is considerable variability in the methane gas fluxes from tank to tank and sample to sample.
- The hardness of the water supply appears to influence the overall flux of carbon dioxide, with soft water systems having higher carbon dioxide gas fluxes.
- A correlation between the GHG emission rates from the septic tank and the liquid temperature was not observed, perhaps as a result of the limited duration of the study.
- The presence or absence of a scum layer had no discernable influence on emission rates of methane and carbon dioxide.
- The carbon (measured as COD) in the septic tank effluent discharged to the soil dispersal system was approximately equal to the amount of carbon being vented (measured as carbon dioxide) from the soil dispersal system.

- Methane generated during the anaerobic digestion process was found in both gaseous and aqueous forms but no relation was found between the gas and liquid phase concentrations.
- Nitrous oxide emission rates from septic tanks were found to be negligible; however nitrous oxide was detected in the gases vented from the soil dispersal system.
- Essentially no gas emissions from the soil surface were measured using flux chambers placed above the soil dispersal system trenches.
- Using the mean methane emission value measured for the septic tanks from this project, an MCF value of 0.22 was calculated.

7.3 Recommendations

Based on the findings of this research, the following recommendations are proposed for future studies of greenhouse gas emissions from septic tank systems:

- Due to the uncertainty in several operational parameters, such as temperature and water hardness, and their influence on the production of septic tank gases, further study in other regions of the country is recommended.
- In this study, only direct GHG emissions from operational septic systems were evaluated. A follow up study quantifying the GHG emissions associated with various septage management practices is needed.
- The soil dispersal systems in this study were well drained and did not have any ponding. The evaluation of soil dispersal systems in other soil types and at different stages of ponding is needed. In addition, studies on alternative soil dispersal systems, such as pressure and drip irrigation systems, are needed.
- Only conventional septic tank systems were evaluated in this study. Additional research is needed to quantify gas emissions from alternative onsite wastewater systems, such as natural treatment systems, packed bed filters, and other aerobic treatment processes.
- A study is needed to evaluate the development of methanogenesis in septic tanks from the time of start-up, with and without inoculation.
- The methods for sampling of gases from ventilation systems should be further developed and refined.
- Further study is needed to develop technologies for the control of GHG emissions from wastewater systems is needed, including soil-based filtration and stand-alone biofiltration processes. Integration of these types of control systems may require slight modifications to the aspects of the building code related to septic tank ventilation systems.
- A study is needed to determine the correlation between the GHG emissions and the septic tank influent quality and loading.
- Further work should be conducted to quantify GHG emissions from all types of wastewater management systems so that accurate models can be developed.

APPENDIX A

COD LOADING PER CUBIC METER CALCULATION IN SEPTIC TANKS

The COD loading into a septic tank was calculated assuming two people per residence and two different tank sizes: 1,000 and 1,500 gallons.

1. Determine the total COD loading per day
   The quantity of COD discharged per person is assumed to be 200 g/capita˙d (Crites and Tchobanoglous, 1998):
   Total COD loading is 400 g/d (for two people)
2. Assuming a tank volume of 1,000 gallons
   (400 g/d) / (3.78 m^3) is equal to 106 g COD/m^3·d
3. Assuming a tank volume of 1,500 gallons
   (400 g/d) / (5.68 m^3) is equal to 70 g COD/m^3·d

4 COD loading ranges between 70 and 106 g/m^3·d

It should be noted that in the above computation the 200 g/capita˙d represents the total COD and it is not differentiated between soluble and particulate COD. Particulate COD is expected to primarily settle out in the septic tank while dissolved COD will primarily leave the septic tank with the effluent flow. The referenced values used in the computations presented in Appendixes A and B are based on typical septic tank systems.

APPENDIX B

ESTIMATE OF METHANE EMISSIONS FROM SEPTIC TANK SYSTEM BASED ON VSS AND COD LOADING

Determine the theoretical amount of methane released per day per person discharging wastewater to a septic tank, which is pumped on a 6 yr interval. Note that for a new tank, there may be a lag in methane production, for example methane production may not occur until spring if the tank is pumped in the winter. Also, some people recommend leaving some sludge in the tank for inoculation to promote methanogenesis.

A. Based on VSS Loading

1. Determine the total VSS loading per day
   The quantity of VSS discharged per person is 35 g/capita˙d (Crites and Tchobanoglous, 1998). The total VSS loading over the 6 yr operational period is 154 kg VSS for 2 people.
2. Determine the effluent VSS discharged from the septic tank
   Effluent VSS can be estimated from the effluent TSS. Typical effluent TSS is 85 mg/L (Crites and Tchobanoglous, 1998), and assuming an effluent VSS to TSS ratio of 0.5, the effluent VSS is 42.5 mg/L. The total VSS loading in the effluent over the 6 yr operational period is 41 kg VSS for 2 people.
3. Estimate the total VSS removed as septage after 6 yr (U.S. EPA, 1994)
   Assume the septage removed has a VSS of 9 g/L and a volume of 4,000 L
   The VSS removed as septage is equal to 36 kg VSS after the 6 yr operational period.
4. Estimate the VSS converted to gas
   The VSS converted to gas is determined by subtracting the effluent VSS loading (41 kg) and the septage VSS (36 kg) remaining in the tank from the influent VSS daily loading (154 kg). The resulting VSS converted to gas is 154 kg – 41 kg – 36 kg = 77 kg (over the 6 yr operational period). Thus, the overall VSS destruction rate in the septic tank is estimated to be 50 percent.
5. Determine the methane produced each day per capita
   Assuming gas production rates of 1 m^3/kg VSS converted, gas composition of 60 percent methane (Tchobanoglous et al., 2003), the methane emission rate is determined to be:
   Methane production = [(77 kg VSS x 1,000 g/kg x 0.6) / (6 yr x 365 d/yr x 2 capita)]
   = 10.6 g/capita·d

B. Based on COD Loading

1. Determine the total COD loading per day
   The quantity of COD discharged per person is 200 g/capita˙d (Crites and Tchobanoglous, 1998):
2. Determine the amount of COD retained in septic tank per day
   Assume 60 percent of the influent COD is retained in the septic tank
   The COD remaining in the tank each day is equal to 120 g/d (200 g/d x 0.6)
3. Estimate the total COD removed as septage after 6 yr
   Assume the septage removed has a COD of 40 g/L (U.S. EPA, 1994) and volume of 4,000 L
   The COD removed as septage is equal to 160,000 g (40 g/L x 4,000 L)
4. Convert total COD in septage to equivalent daily value
   For 6 yr time period, the daily COD value in the septage is equal to 73 g/d [160,000 g/(6 yr x 365 d/yr)]
5. Estimate the COD converted to methane (CH_4)
   The COD converted to gas is the difference of daily loading (120 g/d) and the daily equivalent of COD of the removed septage (73 g/d)
   The COD converted to gas is 47 g/d (120g/d – 73 g/d)
6. Conversion of COD to methane at standard conditions (Tchobanoglous et al., 2003).
   COD of CH_4 is the amount of O_2 needed to oxidize CH_4 to CO_2 and H_2O

   $CH_4 + 2O_2 = CO_2 + H_2O$

   $2(32g\ O_2/mole) = 64\ g\ O_2/mole\ CH_4$
   The volume per mole of CH_4 at standard conditions is 22.4 L. Therefore, the CH_4 equivalent of COD converted under anaerobic conditions is (22.4 L/64 g)
   The conversion of COD to methane is equal to 0.35 L CH_4/ g COD
7. Determine the volume of gas produced each day per capita
   Assume the following conversion factors apply
      Density of CH_4 is equal to 0.67 g/L (Density at 20 °C)
   Methane volume produced is equal to 16.45 L/d [(47 g COD/d)·(0.35 g/L CH_4/ g COD)]
   Mass of CH_4 is 11.0 g/d [(16.45 L/d) (0.67 g/L)]
   The contribution of CH_4 per person is equal to 11.0 g/capita·d

APPENDIX C

ESTIMATE OF METHANE EMISSIONS FROM SEPTIC TANK SYSTEM BASED ON IPCC METHODOLOGY (1996, 2007)

The following estimate was based on the methodology developed in the IPCC guidelines for National Greenhouse Gas Inventories, Chapter 6, Methane Emission from Wastewater. Calculations will be based on per-capita basis.

1. Estimate organically degradable carbon in wastewater (TOW)
   TOW = P x BOD x I X 365, where:
   Where TOW = total organics in wastewater in kg BOD/yr
   P = population
   BOD = U.S. per capita BOD in inventory year (value taken from Table 6.4, Estimated BOD_5 values in domestic wastewater for selected regions and countries. The values are an assessment of the literature. Chapter 6, IPCC, 2006)
   I = correction factor, default value 1.0
   TOW = 1 person x 85 g BOD/capita·d x 1.0 x 0.001 kg/g x 365 d/yr
   TOW = 31.03 kg BOD/capita·yr
2. Calculate the methane CH_4 emission factor (EF_j)
   $EF_j = B_o$ x MCF_j , in kg CH_4/kg BOD
   Where B_o = maximum CH_4 producing capacity in kg CH_4/kg BOD (value taken from Table 6.2, Default maximum methane producing capacity for domestic wastewater. Chapter 6, IPCC 2006)
   MCF_j = methane correction factor for septic tanks (value taken from Table 6.3, Default methane conversion values for domestic wastewater. Chapter 6, IPCC 2006)
   EF_j = 0.6 kg CH_4/kg BOD x 0.5
   EF_j = 0.3 kg CH_4/kg BOD
3. Estimate the per capita CH_4 emission
   Methane emission = TOW x EF_j in g CH_4/capita·d
   CH_4 = (31.03 kg BOD/ capita·yr) (0.3 kg CH_4 /kg BOD)
   9.3 kg CH_4/capita·yr = 25.5 g CH_4/capita·d

Comment:
It should be noted that in the above computation it is assumed that half of all influent BOD is converted anaerobically.

APPENDIX D

ESTIMATE OF METHANE EMISSIONS FROM SEPTIC TANK SYSTEM BASED ON SASSE (1998)

The model presented below was developed by Sasse (1998) based on observations of septic tank operation primarily from developing countries. The model parameters, including BOD_5, water consumption per capita, COD/BOD ratio, septic tank dimensions, and dissolved methane content in water were adjusted to be consistent with typical septic tank design parameters in the U.S.

1. Table 22 from Sasse (1998), wastewater production per capita. The highlighted values in the table were calculated using the following assumptions:
   - Population: 1
   - BOD: 85 g/capita·d (Table 4.12, Crites and Tchobanoglous, 1998)
   - Water consumption: 300 L/capita (Average water used in individual residences, Crites and Tchobanoglous, 1998)
   - COD/BOD: 2.33 (COD and BOD values taken from Table 4.12, Crites and Tchobanoglous, 1998)

Table D-1. Wastewater Production Per Capita.

User	BOD_5 per user	Water consumption per user	COD /BOD_5 ratio	Daily flow of wastewater	BOD_5 conc.	COD conc.
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Given Number	Given g/d	Given L/d	Given mg/L / mg/L	Calc. m^3/d	Calc. mg/L	Approx. mg/L
1	85	300	2.33	**0.3**	**283**	**660**

1.1 Calculation of daily flow of wastewater, m^3/d – Column (5)
Daily Flow of wastewater = number of users x water consumption per user
Daily Flow of wastewater = 1 x 300 L/d x 10^{-3} m^3/L = 0.3 m^3/d

1.2 Calculation of BOD_5 concentration, mg/L – Column (6)
$BOD_5 = BOD_5$ / Daily Flow of wastewater
BOD_5 = (85 g/d) / (0.3 m^3/d) = 283 mg/L

1.3 Calculation of the approximate COD concentration, mg/L – Column (7)
COD = COD / BOD_5 x BOD_5
COD = 2.33 x 283 mg/L = 660 mg/L

2. First row of Table 23 from Sasse (1998), general spread sheet for septic tank, input and treatment data. The highlighted values on the table were calculated using the previous values from Step 1 and assuming 12 hours as the time of most wastewater flow and SS/COD ratio equal to 0.42 mg/L.

Table D-2a. General Spread Sheet for Septic Tank, Input and Treatment Data.

Daily waste water flow	Time of most waste water flow	Max flow at peak hours	COD inflow	BOD_5 inflow
(1)	(2)	(3)	(4)	(5)
Given m^3/d	Given h	Calc. m^3/h	Given mg/L	Given mg/L
0.3	12	**0.025**	660	283
			COD/BOD_5	2.33

Table D-2b. General Spread Sheet for Septic Tank, Input and Treatment Data (Continued).

HRT inside tank	Settleable SS/COD ratio	COD removal	COD outflow	BOD_5 outflow
(6)	(7)	(8)	(9)	(10)
Chosen h	Given mg/L / mg/L	Calc. %	Calc. mg/L	Calc. mg/L
24	0.42	**36%**	**421**	**175**

2.1 Calculation of maximum flow at peak hours, m^3/h – Column (3)
Maximum daily flow = Daily wastewater flow, m^3/d / time of most wastewater flow, hr/d
Maximum daily flow = 0.3 m^3/d / 12 h/d = 0.025 m^3/h

2.2 Calculation of the COD removal, % – Column (8)
To calculate the COD removal, Sasse (1998) propose a factor of 0.6. This factor takes into account that in a septic tank the COD removal rate depends on the amount of settleable solids, their COD content, and the intensity of inoculation of fresh inflow. The COD removal is calculated based on the chosen HRT (24 hr).
COD removal = (SS / COD) / 0.6 x {[(HRT – 3) x (0.15 / 27)] + 0.4}
COD removal = 0.42 / 0.6 x {[24 - 3] x (0.15 / 27)] + 0.4} = 36%

2.3 Calculation of the COD outflow, mg/L – Column (9)
COD outflow = (1 – COD removal rate) x COD inflow
COD outflow = (1 -0.36) x 660 mg/L = 421 mg/L

2.4 Calculation of the BOD removal, %
The equation to calculate the BOD removal is related to Fig. 65 in Sasse (1998), the simplified curve of change in the COD/BOD ratio during anaerobic treatment. The BOD removal is based on the COD removal rate (36%).
For a COD removal less than 0.5, the COD/BOD removal ratio is 1.06
Therefore, BOD removal is (0.36)(1.06) = 0.38 or 38%

2.5 Calculation of the BOD outflow, mg/L – Column (10)
BOD outflow = [1 – (BOD removal)] x BOD
BOD outflow = [1 – (0.38)] x 283 mg/L = 175 mg/L

3. Second row of Table 23 from Sasse (1998), dimensions of septic tank. The highlighted values on the table were calculated using the following assumptions:

- Deslugding interval: 72 months, corresponding to 6 yr pump out interval
- Typical septic tank dimensions:
  - Inner width of 1.25 m
  - Inner length of first chamber of 1.5 m
  - Water depth at outlet point of 1.25 m
  - Length of second chamber of 1 m
- Dissolved methane: 25 percent

Table D-3a. Dimensions of Septic Tank.

Desludging interval	Inner width of septic tank	Minimum water depth at outlet point	inner length of first chamber	
(1)	(2)	(3)	(4)	(5)
Chosen	Chosen	Chosen	Required	Chosen
mo	m	m	m	m
72	1.25	1.25	0.48	1.5

Table D-3b. Dimensions of Septic Tank (Continued) and Biogas Production.

Length of second chamber		Volume including sludge	Actual volume of septic tank	Biogas 70% CH_4 (25% dissolved)
(6)	(7)	(8)	(9)	(10)
Required	Chosen	Required	Check	Calc.
m	m	m^3	m^3	m^3/d
0.24	1	**1.13**	**3.90**	**0.03**
Sludge L/g BOD rem -->		**0.0021**		

3.1 Calculation of sludge volume (Sasse, 1998), sludge L/g BOD remaining

The sludge removal BOD depends on the desludging interval, for this case 72 months.

Sludge removed as BOD = if desludging interval < 120 → 0.005 x 0.5 - [(desludging interval - 36) x 0.002]

Sludge volume= 0.005 x 0.5 – [(72-36) x 0.002] = 0.0021 sludge L/g BOD remaining

3.2 Tank volume required including sludge storage, m^3 – Column (8)

Volume required including sludge storage = 2 x daily flow, m^3/d x HRT, h / 24 h/d x inner width of septic tank chosen, m x inner length of first chamber chosen, m

Volume including sludge = 2 x 0.3 m^3/d x 24 hr / 24 hr/d x 1.25 m x 1.5 m = 1.13 m^3

3.3 Calculation of actual volume of septic tank, m^3 – Column (9)

Actual volume of septic tank = (inner length chosen, m + length of second chamber chosen, m) x (minimum water depth at outlet point chosen, m) x (inner width of septic tanks chosen, m)

Actual volume of septic tank = (1.5 m + 1 m) x 1.25 m x 1.25 m = 3.9 m^3

3.4 Calculation of biogas production, m^3/d –Column (10)

A ratio of COD to methane equal to 0.35 L/g COD at standard conditions was used in the equation proposed by Sasse (1998) to calculate the biogas production.

Biogas production = (COD_{inflow} - $COD_{outflow}$, mg/L) x daily flow, m^3/d x 0.35 L/1000 mg x 70% CH_4 x (100 – 25% dissolved CH_4)

Biogas production = (660 mg/L – 421 mg/L) x 0.3 m^3/d x 0.35 L/1000 mg x 0.7 x (1 – 0.25) = 0.03 m^3/d

4. Calculation of methane production (g/capita·d) using density of methane equal to 0.67 g/L (density at 20°C)

Methane production = biogas production, m^3/d x 10^3 L/m^3 / 1 person

Methane production = 0.03 m^3/d x 10^3 L/m^3 / 1 person = 26.9 L/capita·d x 0.67 g/L =

Methane production = 18 g/capita·d

APPENDIX E

VIAL VACUUMING PROCEDURES

(see Figure E-1)

1. Turn on the pump and then the pressure gauge.
2. Let the pressure stabilize at 12 millitorr (approximate 2.32×10^{-4} psi).
3. Take off the caps on the needles and close all the vials.
4. Insert one vial into each needle.
5. Open the extraction valves and wait approximately 30 sec until the pressure is again at 12 millitorr.
6. Remove the vials from the needles.
7. Repeat steps 4 - 6 for all the vials needed in the sampling event.
8. Turn off the pressure gauge and then the pump.
9. Put the caps back on the needles.

Figure E-1. View of Apparatus Used to Evacuate Vials.

APPENDIX F

SAMPLING FORMS FOR THE DIFFERENT COMPONENTS OF THE SEPTIC SYSTEM

SAMPLING FROM LIQUID SURFACE

Date: ____________________ **Hour:** ____________________

SITE NUMBER ____________________

Sample Volume 24 ml **Time interval** 2 min

CHARACTERISTIC	**INLET**	**OUTLET**
Scum		

Water temperature 0ft_________ 1ft___________ 2ft___________ 3ft__________ 4ft__________

Water temperature 0ft_________ 1ft___________ 2ft___________ 3ft__________ 4ft__________

Inlet (in) outlet (out) Duplicate (D)	**Sample (number)**	**Time**	**Start time (min:sec)**	**Final time (min:sec)**	**Temperature °C**
		0			
		1			
		2			
		3			
		4			
		0			
		1			
		2			
		3			
		4			

Water Quality	**pH**	**Dissolved solids (mg/L)**	**Redox (mV)**
Inlet			
Outlet			

Comments:

SAMPLING FROM SOIL SURFACE

Date: ______ **Hour:** ______

SITE NUMBER ______

Sample Volume 24 ml **Time interval** 10 min

Insert number	Sample (number)	Time	Start time (min:sec)	Final time (min:sec)	Temperature °C
1		0			
		1			
		2			
		3			
2		0			
		1			
		2			
		3			
3		0			
		1			
		2			
		3			
4		0			
		1			
		2			
		3			
5		0			
		1			
		2			
		3			
6		0			
		1			
		2			
		3			

Comments:

Attachment C

SAMPLING FROM VENT SYSTEM

Date: ____________________ **Hour:** ____________________

SITE NUMBER ____________________

Sample Volume 24 ml **Time interval** 2 min

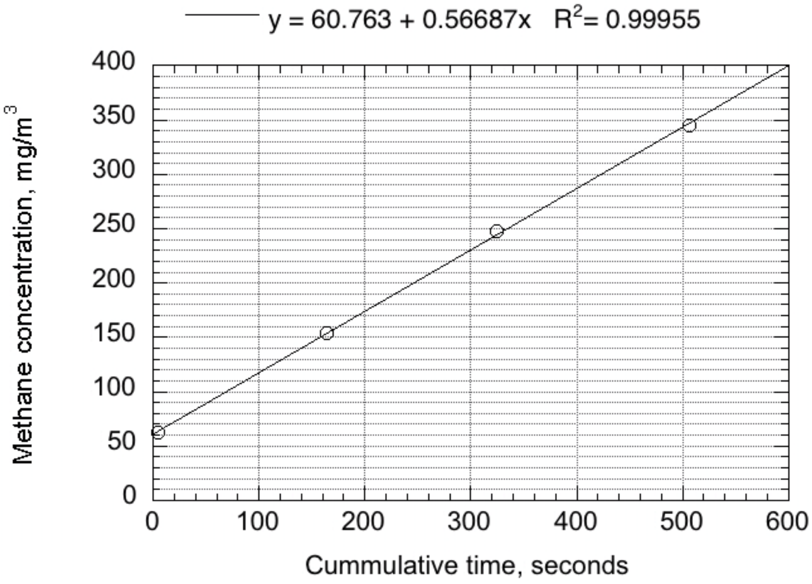
Vent number	Sample (number)	Start time (min:sec)	Final time (min:sec)	Air Velocity (m/s)	Temperature °C
1					
2					

Sample (number)	Pressure (Hpa)	Wind Velocity (m/s)	Outdoor Temperature °C
1			
2			
3			
4			
5			
6			

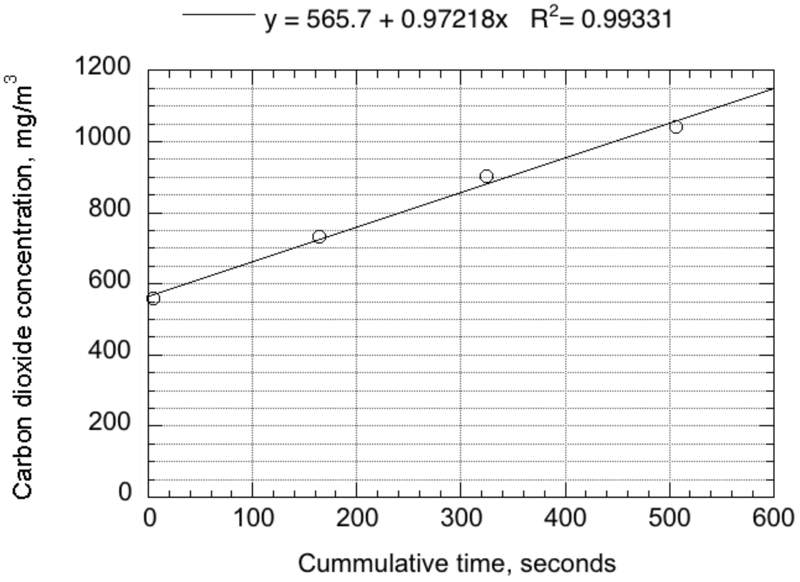
Comments:

APPENDIX G

SAMPLE OF LINEAR FIT FOR METHANE AND CARBON DIOXIDE FLUXES



(a)



(b)

Figure G-1. Sample of Linear Fit for Methane and Carbon Dioxide Fluxes:(a) Methane and (b) Carbon Dioxide Concentration in mg/m^3 Linear Fit.

APPENDIX H

FIELD DATA

H-1 Site 1

This site was characterized for a thin patchy scum layer, less than one inch. Invertebrates were not present on the scum layer. The sludge depth in the first and second compartment was 15 and 8", respectively. The sludge in the first compartment was compacted, very black, while in the second compartment was light and brownish. It was very common to observed turnover episodes. A sampling event was performed after one of the turnover events to determine the influence of these episodes in the gas emissions. The summary of the average GHG emission rates from the septic tank calculated in this site are presented in Table H-1.

Table H-1. Average of GHG Emission Rates From the Septic Tank Liquid Surface.

		Gas measurement (g/capita·d)			Average liquid Temperature (°C)
Date	Sample location	CH_4	CO_2	N_2O	
9/24/09	ST1-1-A[a]	12.00	37.85	0.0	21
	ST1-2-S[b]	6.75	15.25	0.0	22
	ST1-TE[c]	18.75	53.10	0.0	
10/07/09	ST1-1-A	20.71	55.33	0.0	21
	ST1-2-S	8.91	12.68	0.01	21
	ST1-TE	29.62	68.01	0.01	
11/05/09	ST1-1-A	9.17	67.54	0.03	18
	ST1-1-S[d]	27.54	46.09	0.0	18
	ST1-2-S	3.44	14.17	0.0	17
	ST1-TE	12.61	81.71	0.03	
	ST1-TE-1S[e]	30.98	60.26	0.0	
11/10/09	ST1-1-A	32.47	56.33	0.01	17
	ST1-2-S	3.89	17.88	0.0	20
	ST1-TE	36.36	74.21	0.01	

		Gas measurement (g/capita·d)			Average liquid Temperature (°C)
Date	Sample location	CH_4	CO_2	N_2O	
11/12/09	ST1-1-A	14.61	21.87	0.02	16
	ST1-1-S	5.30	25.14	0.0	16
	ST1-2-S	3.11	13.05	0.0	16
	ST1-TE	17.72	34.92	0.02	
	ST1-TE-1S	8.41	38.19	0.0	
11/19/09	ST1-1-A	43.09	52.19	0.01	15
	ST1-1-A-E[f]	12.84	53.89	0.0	15
	ST1-2-S	5.48	10.43	0.0	15
	ST1-TE	48.56	62.62	0.01	
	ST1-TE-1E[g]	18.32	64.32	0.0	
12/03/09	ST1-1-A	7.74	44.60	0.0	14
	ST1-1-S	3.50	15.89	0.0	14
	ST1-2-S	2.21	11.76	0.0	14
	ST1-TE	9.94	56.36	0.0	
	ST1-TE-1S	5.71	27.64	0.0	
Mean value[h]		17.87	57.80	0.00	
Standard deviation[h]		1.94	1.29	5.06	

[a] Septic tank first compartment using insert.

[b] Septic tank second compartment surface. The sample was always taken directly to the liquid surface.

[c] Septic tank total of gas emission rates from both compartments.

[d] Septic tank first compartment surface. The sample was taken directly to the liquid surface.

[e] Septic tank total of gas emission rates using values taken directly to the liquid surface.

[f] Septic tank first compartment using insert after a turnover event.

[g] Septic tank total gas emission rates using the value measured after a turnover event.

[h] Geometric mean and standard deviation values were calculated using the total emission rate value in each date.

Additionally to the gas measurements, several water quality parameters were also measured in both inlet and outlet chambers of the septic tank. The parameters measured included COD, dissolved solids, pH and redox potential. The results of the measurements obtained are summarized in Table H-2.

Table H-2. Summary of the Water Quality Results From Site 1.

		Parameter			
Date	Sample location	COD (mg/L)	pH	Redox potential (mV)	Dissolved solids (mg/L)
11/05/09	ST1-1-M[a]	-	6.69	- 150	465
	ST1-2-M[b]	-	-	-	-
11/12/09	ST1-1-M	-	6.69	- 210	455
	ST1-2-M	-	6.79	- 211	463
11/19/09	ST1-1-M	225	6.80	-170	449
	ST1-2-M	170	6.85	-180	450
12/03/09	ST1-1-M	289	6.83	- 185	473
	ST1-2-M	241	6.82	-206	480
Mean value[c]		257	6.75	-188	459
Standard deviation[c]		45	0.07	20	12
Mean value[d]		206	6.82	-199	464
Standard deviation[d]		-	0.03	17	15

[a] Septic tank first compartment. The samples were taken one foot below the liquid surface.
[b] Septic tanks second compartment. The samples were taken one foot below the liquid surface.
[c] Mean value and standard deviation from the values in the first compartment.
[d] Mean value and standard deviation from the values in the second compartment

Water samples were also collected at both compartments of the septic tank to determine the amount of methane, carbon dioxide and nitrous oxide present in solution. A summary each of the dissolved gases calculated per compartment are presented in Table H-3.

Table H-3. Summary of Dissolved Methane Measured in Each Compartment of the Septic Tank.

		Gas measurement (g/capita·d)		
Date	Sample	Methane	Carbon dioxide	Nitrous oxide
11/12/09	ST1-1-L[a]	2.71	5.63	0.0
	ST1-2-L[b]	1.12	4.55	0.0
11/19/09	ST1-1-L	1.44	5.21	0.02
	ST1-2-L	1.14	6.74	0.02
12/03/09	ST1-1-L	1.65	7.61	0.02
	ST1-2-L	0.06	0.50	0.02
Mean value[a]		1.93	6.15	0.01
Mean value[b]		0.77	3.93	0.01

[a] Septic tank first compartment.
[b] Septic tank second compartment.

After the initial inspections, Site 1 was selected for venting and soil dispersal system sampling. Samples from the vent system were taken at two different cleanout vents located before and after the septic tank. An anemometer was used to determine the air flow inside the vent pipe to calculate the flow rate and therefore the GHG emission rates. The air velocity in the venting pipes ranged from 35 to 100 ft/min. A summary of the average GHG emission rates from the vent system are presented in Table H-4.

Table H-4. Average of GHG Emission Rates From the Vent System.

Date	Sample location	Gas measurement (g/capita·d) CH_4	CO_2	N_2O	Average Temperature (°C)
11/10/09	V-1-1[a]	12.11	710.65	0.49	17
11/12/09	V-1-1	8.43	744.30	0.95	15
	V-1-2[b]	0.03	637.43	0.52	16
11/19/09	V-1-1	9.72	393.03	0.42	15
	V-1-2	0.03	10.93	0.02	14
12/03/09	V-1-1	9.17	533.10	0.42	13
	V-1-2	0.0	69.21	0.09	14
02/05/10	V-1-1	6.49	446.01	0.18	11
	V-1-2	0.06	432.79	0.18	10
Mean value[c]		8.44	527.00	0.37	
Standard deviation[c]		0.01	103.62	0.08	
Mean value[d]		1.27	1.31	1.82	
Standard deviation[d]		6.60	0.97	6.09	

[a] Cleanout vent located before the septic tank.
[b] Cleanout vent located before the soil dispersal system
[c] Geometric mean value and standard deviation calculated to the cleanout vent located before the septic tank
[d] Geometric mean value and standard deviation calculated to the cleanout vent located before the soil dispersal system.

The main soil dispersal system characteristics are summarized in Table H-5. Six 12" inserts were installed to sample from the soil dispersal system. Five were distributed above the system and one was inserted outside the system for control purposes.

Table H-5. General Characteristics of the Soil Dispersal System.

Characteristic	Value	Unit
Area	205	m^2
Slope	20	%
Number of trenches	3	-
Rings installed	6[a]	-

[a] Five distributed on the trenches and one located 10 ft away from the dispersal system area for control purposes.

Gas samples were taken using the flux chamber and were analyzed for methane, carbon dioxide and nitrous oxide. The system was sampled twice to verify the results obtained in the first set of measurements. On the second trial, emission rates of the three GHGs were detected in the control ring and also in two of rings located above the dispersal system. However, the values calculated were similar or less than the control value as seen in Table H-6.

Table H-6. GHG Emission Rates From the Soil Dispersal System.

Date[a]	Sample location	Gas measurement (g/capita·d) CH_4	 CO_2	 N_2O	Average Temperature (°C)
12/03/09	SD1-R1C[b]	0.004	485	0.04	12
	SD1-R2[c]	ND[d]	ND	ND	11
	SD1-R3	ND	ND	0.00	11
	SD1-R4	ND	236	ND	9
	SD1-R5	ND	ND	ND	10
	SD1-R6	ND	671	0.1	10

[a] On 11/12/09 a sampling event was performed at this site. However, fluxes of CH_4, CO_2 and N_2O were not detected in the 5 sampling rings. Control values for CH_4, CO_2 and N_2O in g/capita·d were 0.8, 0 and 0 respectively.

[b] Control ring located on the soil dispersal system.

[c] Sampling ring located on the soil dispersal system.

[d] Flux of gas was not detected.

H-2 Site 2

The scum layer in the first compartment of this septic tank was thick and compacted approximately 4".

Table H-7. Average of GHG Emission Rates From the Septic Tank Liquid Surface.

Date	Sample location	Gas measurement (g/capita·d)			Average liquid Temperature (°C)
		CH_4	CO_2	N_2O	
9/24/09	ST2-1-A[a]	1.04	39.31	0.03	26
	ST2-2-S[b]	3.07	14.18	0.0	26
	ST2-TE[c]	4.11	53.50	0.03	
10/07/09	ST2-1-A	12.34	70.51	0.0	25
	ST2-2-S	0.51	12.71	0.0	24
	ST2-TE	12.85	83.23	0.0	
11/05/09	ST2-1-A	10.77	58.86	0.0	22
	ST2-2-S	1.11	6.53	0.0	20
	ST2-TE	11.88	65.39	0.0	
11/19/09	ST2-1-A	1.56	36.24	0.02	18
	ST2-2-S	2.11	12.52	0.01	18
	ST2-TE	3.67	48.75	0.02	
12/08/09	ST2-1-A	4.81	19.90	0.0	14
	ST2-2-S	17.06	29.16	0.0	14
	ST2-TE	21.87	49.06	0.0	
Mean value[d]		8.72	58.69	0.01	
Standard deviation[d]		2.17	1.26	3.25	

[a] Septic tank first compartment using insert.
[b] Septic tank second compartment using insert.
[c] Septic tank total gas emission rates from both compartments.
[d] Geometric mean value and standard deviation calculated using the total of gas emission rates from both compartments.

It was black with humus like appearance, with larvae and small flies present on the top. The sludge depth in the first and second compartment was 12 and 6", respectively. The summary of the GHG emission rates from the septic tank in this site is presented in Table H-7

Water quality parameters were also measured in both inlet and outlet chambers of the septic tank. The parameters measured included COD, dissolved solids, pH and redox potential. The results of the measurements obtained are summarized in Table H-8.

Table H-8. Summary of the Water Quality Results from Site 2.

		Parameter			
Date	Sample location	COD (mg/L)	pH	Redox potential (mV)	Dissolved solids (mg/L)
11/05/09	ST2-1-M[a]	-	7.24	-241	636
	ST2-2-M[b]	-	7.20	-222	652
11/19/09	ST2-1-M	254	6.87	-195	620
	ST2-2-M	173	7.06	-230	612
12/08/09	ST2-1-M	240	7.02	-190	612
	ST2-2-M	175	7.17	-220	632
Mean value[c]		247	7.04	-209	623
Standard deviation[c]		-	0.19	28.11	12.22
Mean value[d]		174	7.14	-224	632
Standar deviation[d]		-	0.07	5.29	20

[a] Septic tank first compartment. The samples were taken one foot below the liquid surface.
[b] Septic tanks second compartment. The samples were taken one foot below the liquid surface.
[c] Mean value and standard deviation from the values in the first compartment.
[d] Mean value and standard deviation from the values in the second compartment.

Water samples were also collected at both compartments of the septic tank to determine the amount of methane, carbon dioxide and nitrous oxide present in solution. A summary of the dissolved gases calculated per compartment are presented in Table H-9.

Table H-9. Summary of Dissolved Methane Measured in Each Compartment of the Septic Tank.

		Gas measurement (g/capita·d)		
Date	Sample	Methane	Carbon dioxide	Nitrous oxide
11/19/09	ST2-1-L[a]	2.05	7.51	0.02
	ST2-2-L[b]	1.42	4.90	0.02
12/08/09	ST2-1-L	1.59	4.46	0.0
	ST2-2-L	0.004	0.29	0.0
Mean value[a]		1.82	6.23	0.01
Mean value[b]		0.71	2.60	0.01

[a]Septic tank first compartment.
[b] Septic tank second compartment

Site 2 was also selected to be sampled in detail. However, the soil infiltration system was not a good candidate for gas sampling due to the dense vegetation above it. Therefore, gas samples were just taken at the septic tank and vent system. Samples from the vent system were taken at a cleanout vent located before the septic tank. The air velocity of the air in the venting pipes varied from 30 to 80 ft.min. A summary of the GHG emission rates from the vent system is presented in Table H-10.

Table H-10. GHG Emission Rates From the Vent System[a].

		Gas measurement (g/capita·d)			
Date	Sample location	CH_4	CO_2	N_2O	Average Temperature (°C)
9/24/09	V-2-1	18.58	249.03	0.16	19

[a] The vent system was sampled twice. However, during the second trial on December 8th, the vent pipe was frozen (ambient temperature was 6 °C) and the velocity inside the pipe was zero.

H-3 Site 3

In this site gas samples were only taken at the septic tank liquid surface. The scum layer in this site was thick between 3 and 4", but it was not as compacted as the scum layer at Sites 1 and 2. Contrary, this scum layer has a crumbly earth appearance and it was populated by earthworms. The sludge depth in the first and second compartment was 12 and 15", respectively. The summary of the average GHG emission rates from the septic tank calculated in this site is presented in Table H-11.

Table H-11. Average of GHG Emission Rates From the Septic Tank Liquid Surface.

		Gas measurement (g/capita·d)			
Date	Sample location	CH_4	CO_2	N_2O	Average liquid Temperature (°C)
9/24/09	ST3-1-A[a]	0.87	26.06	0.04	27
	ST3-2-A[b]	1.55	20.47	0.0	26
	ST3-TE[c]	2.43	46.53	0.04	
10/07/09	ST3-1-A	24.06	54.66	0.0	23
	ST3-2-A	1.03	7.77	0.01	22
	ST3-TE	25.09	62.43	0.01	
11/05/09	ST3-1-A	12.39	33.39	0.06	19
	ST3-2-A	1.31	9.75	0.01	19
	ST3-TE	13.70	43.14	0.07	
Mean value[d]		9.42	50.04	0.03	
Standard deviation[d]		3.36	1.22	2.38	

[a] Septic tank first compartment using insert.

[b] Septic tank second compartment using insert.

[c] Septic tank total gas emission rates from both compartments.

[d] Geometric mean value and standard deviation calculated using the total gas emission rates from both compartments.

Water quality parameters were also measured in both inlet and outlet chambers of the septic tank. The results of the measurements obtained are summarized in Table H-12.

Table H-12. Summary of the Water Quality Results from Site 3.

		Parameter		
Date	Sample location	pH	Redox potential (mV)	Dissolved solids (mg/L)
11/05/09	ST3-1-M[a]	6.82	-215	499
	ST3-2-M[b]	7.20	-272	755

[a] Septic tank first compartment. The sample was taken one foot below the liquid surface.
[b] Septic tanks second compartment. The sample was taken one foot below the liquid surface.

H-4 Site 4

As soon as the tank lids were opened, a pine odor was detected. The sludge depth in the tank was 14", it had a brownish color and it was very light. The summary of the average GHG emission rates from the septic tank calculated in this site are presented in Table H-13.

Table H-13. Average of GHG Emission Rates from the Septic Tank Liquid Surface.

		Gas measurement (g/capita·d)			Average liquid Temperature (°C)
Date	Sample location	CH_4	CO_2	N_2O	
9/24/09	ST4-1-S[a]	0.55	2.70	0.0	22
	ST4-2-S[b]	0.09	3.39	0.0	22
	ST4-TE[c]	0.63	6.09	0.0	
10/07/09	ST4-1-S	0.17	3.42	0.0	18
	ST4-2-S	0.01	1.87	0.0	19
	ST4-TE	0.17	5.30	0.0	
11/05/09	ST4-1-S	0.06	0.21	0.0	15
	ST4-2-S	0.01	0.89	0.0	15
	ST4-TE	0.07	1.09	0.0	
Mean value[d]		0.20	3.28	0.0	
Standard deviation[d]		3.03	2.60	0.0	

[a] Septic tank first compartment. It was not necessary to install an insert to sample from the first compartment.
[b] Septic tank second compartment. It was not necessary to install an insert to sample from the second compartment.
[c] Septic tank total gas emission rates from both compartments.
[d] Geometric mean value and standard deviation calculated using the total gas emission rates from both compartments.

Water quality parameters were also measured in both inlet and outlet chambers of the septic tank. Measurements were also made to the water supply of the house. The results of the measurements obtained are summarized in Table H-14.

Table H-14. Summary of the Water Quality Results from Site 4.

Date	Sample location	Parameter pH	Redox potential (mV)	Dissolved solids (mg/L)
11/05/09	ST4-1-M[a]	6.70	+131	46
	ST4-2-M[b]	6.26	+216	79
	WSH[c]	8.3	+530	29

[a] Septic tank first compartment. The sample was taken one foot below the liquid surface.
[b] Septic tanks second compartment. The sample was taken one foot below the liquid surface.
[c] Sample taken to the water supply of the house.

H-5 Site 5

The scum layer was black, very thin, around 1 inch, and populated with larvae. Floating toilet paper was very common in this septic tank. The sludge was brownish and very light with a depth of 8 and 6" in the first and second compartment, respectively. The average GHG emission rates from the septic tank calculated in this site are presented in Table H-15.

Table H-15. Average of GHG Emission Rates from the Septic Tank Liquid Surface.

Date	Sample location	Gas measurement (g/capita·d) CH_4	CO_2	N_2O	Average liquid Temperature (°C)
9/24/09	ST5-1-A[a]	3.01	13.65	0.0	25
	ST5-2-S[b]	1.23	5.79	0.0	24
	ST5-TE[c]	4.25	19.44	0.0	
10/07/09	ST5-1-A	4.94	27.02	0.0	21
	ST5-2-S	0.66	3.86	0.0	21
	ST5-TE	5.59	30.88	0.0	
11/05/09	ST5-1-A	9.88	39.66	0.0	17
	ST5-2-S	0.64	4.23	0.02	16
	ST5-TE	10.52	43.89	0.02	
Mean value[d]		6.30	29.76	0.01	
Standard deviation[d]		1.59	1.40	1.59	

[a] Septic tank first compartment using insert.
[b] Septic tank second compartment. It was not necessary to install an insert to sample in the second compartment.
[c] Septic tank total gas emission rates from both compartments.
[d] Geometric mean value and standard deviation calculated using the total gas emission rates from both compartments.

Water quality parameters were also measured in both inlet and outlet chambers of the septic tank. The results of the measurements obtained are summarized in Table H-16.

Table H-16. Summary of the Water Quality Results from Site 5.

Date	Sample location	Parameter pH	 Redox potential (mV)	 Dissolved solids (mg/L)
11/05/09	ST5-1-M[a]	7.05	-205	690
	ST5-2-M[b]	7.42	-223	749

[a] Septic tank first compartment. The sample was taken one foot below the liquid surface.

[b] Septic tanks second compartment. The sample was taken one foot below the liquid surface.

H-6 Site 6

A thick scum layer of around 3" was observed in the liquid close the inlet tee; however the rest of the tank had a patchy brownish scum layer. The outlet water surface had a thin oily layer. The sludge depth measured in the first and second compartment was 6 and 20", respectively. The summary of the average GHG emission rates from the septic tank calculated in this site are presented in Table H-17.

Table H-17. Average of GHG Emission Rates from the SepticTank Lquid Surface.

Date	Sample location	Gas measurement (g/capita·d) CH_4	 CO_2	 N_2O	Average liquid Temperature (°C)
9/24/09	ST6-1-A[a]	8.31	17.37	0.01	22
	ST6-2-A[b]	1.64	13.39	0.0	22
	ST6-TE[c]	9.95	30.76	0.01	
11/05/09	ST6-1-A	5.79	60.02	0.0	16
	ST6-2-A	1.64	11.40	0.0	15
	ST6-TE	7.43	71.42	0.0	
Mean value[d]		8.60	46.87	0.0	
Standard deviation[e]		1.23	1.82	1.48	

[a] Septic tank first compartment using insert.

[b] Septic tank second compartment using insert.

[c] Septic tank total gas emission rates from both compartments.

[d] Geometric mean value calculated using the total gas emission rates from both compartments.

[e] Geometric standard deviation calculated using the total gas emission rates from both compartments.

Water quality parameters were also measured in both inlet and outlet chambers of the septic tank. The results of the measurements obtained are summarized in Table H-18.

Table H-18. Summary of the Water Quality Results from Site 6.

Date	Sample location	pH	Redox potential (mV)	Dissolved solids (mg/L)
		Parameter		
11/05/09	ST6-1-M[a]	6.93	-212	673
	ST6-2-M[b]	6.98	-197	691

[a] Septic tank first compartment. The sample was taken one foot below the liquid surface.
[b] Septic tanks second compartment. The sample was taken one foot below the liquid surface

H-7 Site 7

The scum layer had an approximate thickness of 3", and it tend to accumulates in the around the inlet tee. The scum was black, had a crumbly earth appearance in some spots and it was populated by larvae and small flies. The sludge depth in the first and second compartment was 14 and 6 ", respectively. The summary of the average GHG emission rates from the septic tank calculated in this site are presented in Table H-19.

Water quality parameters were also measured in both inlet and outlet chambers of the septic tank. The parameters measured included COD, dissolved solids, pH and redox potential. The results of the measurements obtained are summarized in Table H-20.

Table H-19. Average of GHG Emission Rates from the Septic Tank Liquid Surface.

		Gas measurement (g/capita·d)			
Date	Sample location	CH_4	CO_2	N_2O	Average liquid Temperature (°C)
10/07/09	ST7-1-A[a]	5.35	23.75	0.0	21
	ST7-2-A[b]	0.89	6.0	0.0	20
	ST7-TE[c]	6.24	29.75	0.0	
11/05/09	ST7-1-A	24.23	36.01	0.0	16
	ST7-2-A	0.79	2.92	0.0	17
	ST7-TE	25.01	38.93	0.0	
11/17/09	ST7-1-A	19.20	43.09	0.0	17
	ST7-2-A	0.58	7.19	0.0	16
	ST7-TE	19.78	50.28	0.0	
12/01/09	ST7-1-A	26.25	50.56	0.02	15
	ST7-2-A	0.58	5.52	0.0	14
	ST7-TE	26.83	56.07	0.02	
Mean value[d]		16.97	42.51	0.0	
Standard deviation[d]		1.86	1.33	-	

[a] Septic tank first compartment using insert.
[b] Septic tank second compartment using insert.
[c] Septic tank total gas emission rates from both compartments.
[d] Geometric mean value and standard deviation calculated using the total gas emission rates from both compartments.

Table H-20. Summary of the Water Quality Results from Site 7.

		Parameter			
Date	Sample location	COD (mg/L)	pH	Redox potential (mV)	Dissolved solids (mg/L)
11/05/09	ST7-1-M[a]	-	6.61	-201	649
	ST7-2-M[b]	-	6.89	-180	682
11/17/09	ST7-1-M	-	6.52	-170	560
	ST7-2-M	-	6.74	-220	590
12/01/09	ST7-1-M	408	6.56	-196	607
	ST7-2-M	306	6.69	-195	604
Mean value[c]		-	6.56	-189	605
Standard deviation[c]		-	0.05	17	45
Mean value[d]		-	6.77	-198	625
Standard deviation[d]		-	0.10	20	50

[a] Septic tank first compartment. The sample was taken one foot below the liquid surface.
[b] Septic tanks second compartment. The sample was taken one foot below the liquid surface.
[c] Mean value and standard deviation from the values in the first compartment.
[d] Mean value and standard deviation from the values in the second compartment.

Water samples were also collected at both compartments of the septic tank to determine the amount of methane, carbon dioxide and nitrous oxide present in solution. A summary of the dissolved gases calculated per compartment are presented in Table H-21.

Table H-21. Summary of Dissolved Methane Measured in Each Compartment of the Septic Tank.

		Gas measurement (g/capita·d)		
Date	Sample	Methane	Carbon dioxide	Nitrous oxide
11/17/09	ST7-1-L[a]	0.29	1.88	0.01
	ST7-2-L[b]	0.0	0.17	0.01
12/01/09	ST7-1-L	0.94	6.6	0.0
	ST7-2-L	0.0	0.18	0.0
Mean value[a]		0.61	4.24	0.005
Mean value[b]		0.0	0.17	0.0

[a] Septic tank first compartment.
[b] Septic tank second compartment

Site 7 was selected to be sampled in more detailed. Therefore, gas samples were taken at the septic tank, vent and soil dispersal systems. Samples from the vent system were taken at the cleanout vent located before the septic tank. Air velocity measured in the passive house venting systems ranged from 40 to 100 ft/min when an effluent filter was not present. Effluent filters reduced the air flow through the vent system to a range of 0 to 0.1 m/s (0 to 10 ft/min). The results from the vent systems measurements are summarized in Table H-22.

Table H-22. GHG Emission Rates from the Vent System.

Date	Sample location	Gas measurement (g/capita·d)			Average Temperature (°C)
		CH_4	CO_2	N_2O	
11/17/09	V7-1EF[a]	31.73	192.56	0.21	14
12/01/09	V7-1EF	7.53	57.73	0.01	17
	V7-1OF[b]	5.51	36.18	0.0	13
	V7-1WEF[c]	14.89	115.75	0.02	12
Mean value[a]		13.39	93.47	0.04	

[a] The vent system samples were typically taken without opening the tank lids and with the installed effluent filter. The mean was calculated using the results from the two sampling events performed in this conditions.

[b] Vent sample taken using a biotube effluent filter model FTi0418-S from Orenco Systems, Inc.

[c] Vent sample taken without the effluent filter and tank lids off.

The main soil dispersal system characteristics are summarized in Table H-23. Six 12" inserts were installed to sample from the soil dispersal system. Five were distributed above the system and one was inserted outside the system for control purposes.

Table H-23. General Characteristics of the Soil Dispersal System.

Characteristic	Value	Unit
Area	650	m^2
Slope	8.5	%
Number of trenches	3	-
Rings installed	6[a]	-

[a] Five distributed on the trenches and one located 6 ft away from the dispersal system area for control purposes.

Gas samples were taken and analyzed for methane, carbon dioxide and nitrous oxide. During the first set of measurements, methane gas was detected once in one of the rings but not in the control one. In the second sampling date, the carbon dioxide emission rates values were similar or less than the control value and nitrous oxide emission rates were double than the control value but the amount is not significant. A summary of the results from the soil dispersal system at Site 7 are found in Table H-24.

Table H-24. GHG Emission Rates from the Soil Dispersal System.

Date	Sample location	Gas measurement (g/capita·d) CH_4	CO_2	N_2O	Average Temperature (°C)
11/17/09	SD7-R1[a]	ND[c]	ND	ND	16.8
	SD7-R2C[b]	ND	619	0.19	14.8
	SD7-R3	ND	ND	ND	17.2
	SD7-R4	ND	110	0.11	19.4
	SD7-R5	ND	ND	ND	19.1
	SD7-R6	0.0	ND	0.10	16.5
12/01/09	SD7-R1	ND	842	0.07	16.8
	SD7-R2C	ND	843	0.04	14.8
	SD7-R3	0.09	469	0.11	17.2
	SD7-R4	ND	ND	ND	19.4
	SD7-R5	ND	ND	0.5	19.1
	SD7-R6	ND	851	0.16	16.5

[a] Sampling ring located on the soil dispersal system.
[b] Control ring located on the soil dispersal system.
[c] Flux of gas was not detected.

H-8 Site 8

The scum layer in this septic tank was thin, less than one inch, it was black and small larvae were observed in both compartments. The sludge depth both compartments of the septic tank was 3' and it had a very thick consistency. The total water depth was 5'. therefore the clear zone of the tank was reduced to 2'. The tank has a strong odor compared to the tanks in ALT. A summary of the GHG emission rates from the septic tank calculated in this site are shown in Table H-25.

Table H-25. Average of GHG Emission Rates from the Septic Tank Liquid Surface.

Date	Hour	Sample location	Gas measurement (g/capita·d) CH_4	CO_2	N_2O	Average liquid Temperature (°C)
10/21/09	11:00 am	ST8-1-A[a]	9.88	46.58	0.0	17
		ST8-2-A[b]	1.10	8.31	0.0	17
		ST8-TE[c]	10.98	54.89	0.0	
	3:00pm	ST8-1-A	10.96	25.59	0.0	17
		ST8-2-A	1.14	6.36	0.0	17
		ST-8-TE	12.10	31.94	0.0	
	7:00pm	ST8-1-A	1.14	13.51	0.0	16
		ST8-2-A	2.80	1.97	0.0	16
		ST8-TE	3.44	15.48	0.0	
	11:00pm	ST8-1-A	73.72	33.54	0.0	16
		ST8-2-A	1.95	12.57	0.0	16
		ST8-TE	75.68	46.21	0.0	
10/22/09	3:00 am	ST8-1-A	10.06	74.54	0.0	16
		ST8-2-A	1.21	1.00	0.0	16

Date	Hour	Sample location	Gas measurement (g/capita·d)			Average liquid Temperature (°C)
			CH_4	CO_2	N_2O	
		ST8-TE	11.27	75.54	0.0	
	7:00 am	ST8-1-A	34.41	10.92	0.0	16
		ST8-2-A	1.48	17.45	0.0	16
		ST8-TE	35.89	28.37	0.0	
	11:00am	ST8-1-A	ND[d]	ND	ND	17
		ST8-2-A	4.05	5.52	0.02	17
		ST8-TE	4.05	5.52	0.02	
12/10/09	7:30 am	ST8-1-A	1.33	12.35	0.01	13
		ST8-2-A	1.38	2.43	0.0	13
		ST8-TE	2.72	14.77	0.01	
	11:00 am	ST8-1-A	2.70	1.62	0.01	13
		ST8-2-A	1.42	2.17	0.0	13
		ST8-TE	4.11	3.79	0.01	
	2:00pm	ST8-1-A	10.24	1.80	0.0	13
		ST8-2-A	0.98	0.72	0.01	13
		ST8-TE	11.23	2.53	0.01	
	7:00pm	ST8-1-A	0.34	0.54	0.0	13
		ST8-2-A	0.68	0.73	0.01	13
		ST8-TE	1.02	1.26	0.01	
12/11/09	8:00am	ST8-1-A	4.63	1.74	0.0	12
		ST8-2-A	1.03	0.86	0.0	12
		ST8-TE	5.66	2.60	0.0	
Mean value[e]			8.99	12.58	0.01	
Standard deviation[e]			3.33	3.9	4.42	

[a] Septic tank first compartment using insert.

[b] Septic tank second compartment. The flux chamber was installed directly to the liquid surface.

[c] Septic tank total gas emission rates from both compartments.

[d] Not detected.

[e] Geometric mean value and standard deviation calculated using the total gas emission rates.

Water quality parameters were also measured in both inlet and outlet chambers of the septic tank. The parameters measured included COD, dissolved solids, pH and redox potential. The results of the measurements obtained are summarized in Table H-26.

Table H-26. Summary of the Water Quality Results from Site 5[a].

		Parameter			
Date	Sample location	COD (mg/L)	pH	Redox potential (mV)	Dissolved solids (mg/L)
12/10/09	ST7-1-M[a]	164	7.66	-	1113
	ST7-2-M[b]	108	7.57	-212	1200
12/11/09	ST7-1-M	168	-	-	-
	ST7-2-M	112	-	-	-

[a] Septic tank first compartment. The sample was taken one foot below the liquid surface.

[b] Septic tanks second compartment. The sample was taken one foot below the liquid surface.

Water samples were also collected at both compartments of the septic tank to determine the amount of methane present in solution. A summary of the dissolved methane calculated per compartment are shown in Table H-27.

Table H-27. Summary of Dissolved Methane Measured in Each Compartment of the Septic Tank.

		Gas measurement (g/capita·d)		
Date	Sample	Methane	Carbon dioxide	Nitrous oxide
12/10/09	ST8-1-L[a]	0.50	2.14	0.002
	ST8-2-L[b]	0.33	1.61	0.001
12/11/09	ST8-1-L	0.55	2.72	0.002
	ST8-2-L	0.42	2.39	0.001
Mean value[a]		0.52	2.43	0.002
Mean value[b]		0.38	2.00	0.001

[a] Septic tank first compartment.

[b] Septic tank second compartment.

H-9 Summary of Results

A summary of the sampling dates, calculated average GHG emission rates value and the standard deviation from the different septic tanks studied is presented in Table H-28.

Table H-28. Summary of GHG Emission Rates from the Eight Septic Tanks Used in the Study.

Septic tank number	Gas Measurement (g/capita•d)					
	CH_4		CO_2		N_2O	
	TGE[a]	SD[b]	TGE	SD	TGE	SD
1	17.87	1.94	57.80	1.29	0.0	5.06
2	8.72	2.17	58.69	1.26	0.01	3.25
3	9.42	3.36	50.04	1.22	0.03	2.38
4	0.20	3.03	3.28	2.60	0.0	0.0
5	6.30	1.59	29.76	1.40	0.01	1.59
6	8.60	1.23	46.87	1.82	0.0	1.48
7	16.97	1.86	42.51	1.33	0.0	-
8	8.99	3.33	12.58	3.90	0.01	4.42

[a] Mean value of total gas emission rates from both compartments.
[b] Standard deviation calculated to the total gas emission rates from both compartments.

APPENDIX I

CALCULATION OF COD IN TERMS OF CO_2 FOR MASS BALANCE ON THE SOIL DISPERSAL SYSTEM

1. Balanced oxidation equation for wastewater
   $2C_{10}H_{19}O_3N + 25\,O_2 = 20CO_2 + 16H_2O + 2NH_3$
   (221 g/mol) (32 g/mol) (44g /mol)

2. Theoretical (chemical) oxygen demand for $C_{10}H_{19}O_3N$
   (25 x 32)/(2 x 221) = 1.81 g O_2/ g $C_{10}H_{19}O_3N$ = 1.81 g COD/ g $C_{10}H_{19}O_3N$

3. Carbon dioxide equivalent for $C_{10}H_{19}O_3N$
   (20 x 44)/(2 x 221) = 1.99 g CO_2/ g $C_{10}H_{19}O_3N$

4. Carbon dioxide produced from COD
   (1.99 g CO_2 / g $C_{10}H_{19}O_3N$) / (1.81 g COD / g $C_{10}H_{19}O_3N$) = 1.1 g CO_2/g COD

5. COD value measured at the effluent equal to 206 mg/L, assuming that the flow coming to the septic tank ranges from 200 to 590 L/capita·d (Crites and Tchobanoglous, 1998; GDPUD, 2010), the COD in terms of CO_2 is calculated.

   (206 mg COD/L) / (1 g/1000 mg) x (200 L/d) x (1.1 g CO_2/g COD)
   = 45.3 g CO_2/capita·d

   (206 mg COD/L) / (1 g/1000 mg) x (590 L/d) x (1.1 g CO_2/g COD)
   = 133.7 g CO_2/capita·d

Thus, the CO_2 equivalent of the COD loading to the soil dispersal system is expected to range 45.3 to 133.7 g CO_2/capita·d.

REFERENCES

Aneja, V.P., J. Blunden, C.S. Clairborn, and H.H. Rogers (2006) *"Dynamic Chamber System to Measure Gaseous Compounds Emissions and Atmospheric-Biospheric Interactions,"* I. Barnes and K.J. Rudzinski (eds.), Environmental Simulation Chambers: Application to Atmospheric Chemical Processes, 97-109, Netherlands.

Ball, H. (2009) Personal communication.

Bogner, J., R. Pipatti, S. Hashimoto, C. Diaz, K. Mareckova, L. Diaz, P. Kjeldsen, S. Monnis, A. Faaij, Q. Gao, T. Zhang, M.S. Ahmed, R.T.M. Sutamihardja, and R. Gregory (2008) "Mitigation of Global Greenhouse Gas Emissions from Waste: Conclusions and Strategies from the Intergovernmental Panel on Climate Change (IPCC). Fourth Assessment Report. Working Group III (Mitigation)," *J. Waste Management and Research.,* **26**, 11-32.

Bounds, T.R. (1997) "Design and Performance of Septic Tanks," in M.S. Bedinger, J.S. Fleming, and A.I. Johanson (eds.), *Site Characterization and Design of On-Site Septic Systems*, ASTM STP 11324, American Society for Testing and Materials.

Bitton, G. (2005) *Wastewater Microbiology*, 3rd ed., Jhon Wiley & Sons, Inc., Hoboken, New Jersey.

California Plumbing Code (2007) IAPMO. *Chapter Nine, Vents*. Ontario, CA.
Cakir, F.Y. and M.K. Stenstrom (2005) "Greenhouse Gas Production: A Comparison Between Aerobic and Anaerobic Wastewater Treatment Technology," *Water Res.,* **39**, 4197-4203.

Chandran, K. (2009) "Characterization of Nitrogen Greenhouse Gas Emissions from Wastewater Treatment BNR Operations," *Field Protocol with Quality Assurance Plan,* Water Environment Research Foundation, Alexandria, VA.

Christensen, S., P. Ambus, J.R.M. Arah, H. Clayton, B. Galle, D.W.T. Griffith, K.J. Hargreaves, K.A. Smith, M. Welling, and F.G. Wienholds (1996) *"Nitrous Oxide Emissions from an Agricultural Field: Comparison Between Measurements by Flux Chamber and Micrometerological Techniques," Atmospheric Environment*, **30**,24, 4183-4190.

Crites, R. and G. Tchobanoglous (1998) *Small and Decentralized Wastewater Management Systems,* McGraw-Hill, New York.

Dale, R. (1982) *"The Arthropod and Related Fauna of Septic Tanks in Novato, Marin County, California,"* Master thesis, Department of Biology, California State University, Hayward, CA.

D'Amato, V.A., A. Bahe, T.R. Bounds, B. Comstock, T. Konsler, S.K. Liehr, S.C. Long, K. Ratanaphuks, C.A. Rock, and K. Sherma (2008) "Factors Affecting the Performance of Primary

Treatment in Decentralized Wastewater Treatment Systems," Water Environment Research Foundation, Alexandria, VA.

DeSutter, T.M. and J.M. Ham (2005) "Emissions and Carbon Balance Estimates of a Swine Production Facility," *J. Environ. Qual*. **34**,198-206.

Dunbar, W.P. (1908) *Principles of Sewage Treatment*, Translated by H.T. Calvert. Charles Griffin and Co., Ltd., England.

Duncan, M. and N. Horan (2003) *Handbook of Water and Wastewater Microbiology,* Academic Press, ELSEVIER, San Diego, CA.

Erickson, J. and E.J. Tyler (2000) *A Model for Soil Oxygen Delivery to Wastewater Infiltration Surfaces,* NOWRA 2000 Conference Proceedings. National Onsite Wastewater Recycling Association, pp. 91-96.

Foley, J. and P. Lant (2009) *Direct Methane and Nitrous Oxide Emissions from Full-Scale Wastewater Treatment Systems*, The University of Queensland, Australia. Water Services Association of Australia (WSAA) Occasional Paper, No. 24.

GDPUD (2009) Georgetown Divide Public Utility District, Personal communication with D. Creeks.

GDPUD (2010) Georgetown Divide Public Utility District, Personal communication with B. Siren.

Höglund, C. (2001). "*Evaluation of Microbial Health Risks Associated with the Reuse of Source Separated Human Urine,"* Ph.D. thesis, Department of Biotechnology, Royal Institute of Technology, Stockholm, Sweden.

Hutchinson, G.L. and G.P. Livingston (1993) "Use of Chamber Systems to Measure Trace Gas Fluxes," in L.A. Harper, A.R. Moiser, J.M. Duxbury, and D.E. Rolston (eds.) *Agricultural Ecosystem Effects on Trace Gases and Global Climate Change*, ASA Spec. Publ. 55. ASA, Madison, WI.

IPCC (1996) Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.), Cambridge University Press, Cambridge, United Kingdom.

IPCC (2007) Climate Change (2007) Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri, and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland.

Isa, Z., S. Grusenmeyer, and W. Verstraete (1986) "Sulfate Reductions Relative to Methane Production in High-Rate Anaerobic Digestion: Technical Aspects," *J. Applied and Environmental Microbiology.,* **51**,3, 572-579.

Janna, W.S. (2007) *Conduction Shape Factor Method Applied to the Modeling of Oxygen Diffusion Through Soil*, Eleventh Individual and Small Community Sewage Systems Conference Proceedings, 20-24 October 2007, Warwick, Rhode Island, USA, ASAE, St. Josephs, MI.

Kinnicutt, L.P., C.E.A. Winslow, and R.W. Pratt (1910) *Sewage Disposal*, John Wiley and Sons. New York.

Knowles, R. (1993) "Methane: Processes of Production and Consumption," in L.A. Harper, A.R. Moiser, J.M. Duxbury, and D.E. Rolston (eds.) *Agricultural Ecosystem Effects on Trace Gases and Global Climate Change*, ASA Spec. Publ. 55. ASA, Madison, WI.

Leverenz, H., G. Tchobanoglous, and J.L. Darby (2009) "Clogging in Intermittently Dosed Sand Filters Used For Wastewater Treatment," *Water Research,* **43**, 3, 695-705.

Maier, R.M., I.L. Pepper, and C.P. Gerba (2009) *Environmental Microbiology,* 2nd ed., academic Press, ELSEVIER Inc., London.

Maillacheruvu, K.Y. and G.F. Parkin (1996) "Kinetics of Growth, Substrate Utilization, and Sulfide Toxicity for Propionate, Acetate and Hydrogen Utilizers in Anaerobic Systems," *Water Environmental Research,* **68**, 7, 1099-1106.

McCarty, P.L. (1964) "Anaerobic Waste Treatment Fundamental," *Public Works*, **95,** 9, 107 112,10, 123-126, 11, 91-94, 12, 95-99.

McCarty, P.L. (2001) "The Development of Anaerobic Treatment and Its Future," *Water Sci. Tech.,* **44**, 8, 149-155.

Moore, T.R. and N.T. Roulet (1991) "A Comparison of Dynamic and Static Chambers for Methane Emissions Measurements From Subartictic Fens*," Atmos. Ocean,* **29,** 1**,** 102-109.

Patel, G.B., A.W. Khan, and L.A. Roth (1978) "Optimum Levels of Sulfate and Iron for the Cultivations of Pure Cultures of Methanogens in Synthetic Media," *J.Applied Microbiology,* **45**, 347-356.

Parkin, G.F. and R.E. Speece, (1982) "Modeling Toxicity in Methane Fermentation Systems," *J. Environmental Engineering Division,* **108**, 515-531.

Parkin, G.F., N.A. Lynch, WC. Kuo, E.L. Van Keuren, and S.K., Bhattacharya (1990) "Interactions between Sulfate Reducers and Methanogens Fed Acetate and Propionate," *J. Water Pollutions Control Federation,* **62**, 6, 780-788

Perkins, R.J. (1989) *Onsite Wastewater Disposal*, National Environmental Health Association, Lewis Publishers Inc., Ann Arbor, MI.

Philip, H., S. Maunoir, A. Rambaud, and S. Philippi (1993) "Septic Tank Sludge: Accumulation Rate Biochemical Characteristics," Proceedings of the Second International Specialized Conference on Design and Operation of Small Wastewater Treatment Plants, Norway.

Rittmann, B.E. and P.L. McCarty (2001) *Environmental Biotechnology: Principles and Applications,* McGraw-Hill, Inc. New York.

Roy, C. and J.-P. Dubé (1994) "*A Recirculating Gravel Filter for Cold Climates,*" Proceedings of the Seventh International Symposium on Individual and Small Community Systems, American Society of Agricultural Engineers, St. Joseph, MI.

Sahely, H.R., H.L. Maclean, H.D Monteith, and D.M. Bagley (2006) "Comparison of On-site and Upstream Greenhouse Gas Emissions from Canadian municipal wastewater treatment facilities," *J. Environ. Engr. Sci.,* **5**, 405-415.

San Luis Obispo County (2008) *Technical Memorandum, Septage Receiving Station Options*, Los Osos Wastewater Project Development. Los Osos, CA.

Sasse, L. (1998) DEWATS, Decentralized Wastewater Treatment in Developing Countries, Borda, Delhi, India.

Schönheit, P., J.K. Kristjansson, and R.K. Thauer (1982) "Kinetic Mechanism for the Ability of Sulfate Reducers to Out-Compete Methanogens for Acetate," *Arch. Microbiol.,* **132**, 285-288.

Seabloom, R.W., T.R. Bounds, and T.L. Loudon. (2005). Septic Tanks Text. in (M.A. Gross and N.E. Deal, eds.) "University Curriculum Development for Decentralized Wastewater Management," National Decentralized Water Resources Capacity Development Project. University of Arkansas, Fayetteville, AR.

SLOC (2008) San Luis Obispo County septic tank regulation.

Speece, R.E. (1996) *Anaerobic Biotechnology for Industrial Wastewaters.* Archae Press, Nashville, TN.

Tabachow, R.M., P.A. Roelle, J. Peirce, and V.P. Aneja (2002). "Soil Nitric Oxide Emissions: Lab and Field Measurements Comparison," *Environ. Engr. Sci.,* **19**, 4.

Tchobanoglous, G. and E.D. Schroeder (1985) *Water Quality: Characteristics, Modeling and Modification.* Addison-Wesley Company, Inc., Menlo Park, CA.

Tchobanolgous, G. and F.L. Burton (1991) *Wastewater Engineering: Treatment, Disposal, and Reuse*, 3rd ed., McGraw-Hill, Inc., New York.

Tchobanoglous, G., F.L. Burton, and H.D. Stensel (2003) *Wastewater Engineering: Treatment and Reuse*, 4th ed., Metcalf and Eddy, Inc., McGraw-Hill Book Company, New York.

U.S. EPA (1993)*, The Determination of Chemical Oxygen Demand by Semi-Automated Colorimetry,* EPA Method 410.4, Cincinnati, OH.

U.S. EPA (1994) *Guide to Septage Treatment and Disposal,* EPA/625/R-94/002. Washingtion, D.C.

U.S. EPA (1999) *Quantification of Methane Emissions and Discussion of Nitrous Oxide and Ammonia Emissions from Septic Tanks, Latrines and Stagnant Sewers in the World,* EPA-600/R-99-089. Springfield, VA.

U.S. EPA (2000) *Decentralized Systems Technology Fact Sheet. Septic System Tank*, EPA-832-F-00-040. Washington, D.C. September, 2000.

U.S. EPA (2002) *Onsite Wastewater Treatment Systems Manual*, EPA-625/R-00/008, February, 2002.

U.S. EPA (2005) *A Homeowner's Guide to Septic Systems*, EPA-832-B-02-005. U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2009) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007*, EPA 430-R-09-004, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2010) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*, EPA 430-R-10-006, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA Region 9 (2003) California Wastewater Training and Research Center, 2003. Status Report, Onsite Wastewater Treatment Systems in California. California State University, Chico, CA.

U.S. PHS (1957) *Manual of Septic Tank Practice*, U.S. Public Health Service, Washington, DC.

Walker, H.B. and R.H. Driftmier (1929) "Studies of the Septic Tank Method of Sewage Disposal for Isolated Homes," *J. Ag. Engr*., **10**, 8, 9, and 10.

Weibel, S.R., C.P. Straub, and S.A. Thoman (1949) *Studies on Household Sewage Disposal Systems*, Part I. US Public Health Service, Cincinnati, OH.

Weibel, S.R., C.P. Straub, and S.A. Thoman (1955) *Studies on Household Sewage Disposal Systems*, Part III. US Public Health Service, Cincinnati, OH.

Wilhelm, S.R., S.L. Schiff, and J.A. Cherry (1994) "*Biogeochemical Evolution of Domestic Wastewater in Septic Systems: 1. Conceptual Model," J.Ground Water,* ***32****, 6, 905-916.*

Winfrey, M.R. and J.G. Zeikus (1977) "Effect of Sulfate on Carbon and Electron Flow During Microbial Methanogenesis in Freshwater Sediments," *J. Applied and Environmental Microbiology,* ***33****, 2, 275-281.*

Winneberger, J.H.T. (1984) *Septic-tank Systems A Consultant's Toolkit. Volume II- The Septic Tank*. The Butterworth Group, Ann Arbor, MI.

http://cfpub.epa.gov/owm/septic/search.cfm#glossary. Accessed on 08/04/09.

http://www.epa.gov/ncea/iris/subst/0061.htm, Last updated on Thursday, July 9th, 2009. Accessed on 08/19/09.

http://www.epa.gov/nitrousoxide/sources.html, Last updated on Thursday, July 20th, 2009. Accessed on 11/02/09.

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July 2010

Comments Received during the Public Review Period on the "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010."

Commenter: T. J. Blasing, ORNL

Comment: *While looking at your international bunker fuels estimates on page ES-5 I noticed the footnote indicator after International Bunker Fuels should be c; not b.*

Commenter: Erik Colville

Comment: *Please stop wasting taxpayer money inventorying gasses that are not pollutants, do no harm to our environment or humanity, and even if they were reduced would do nothing measurable to affect climate change. What an embarrassing waste of public resources!*

Commenter: The Fertilizer Institute

Comment: *TFI thanks the Agency for the opportunity to present comments on those sections in the Draft Inventory that specifically describe the fertilizer industry. TFI feels that the review process has played a vital role in maintaining the high quality of the inventory. TFI has evaluated the chapters and annexes specifically related to our industry, including changes since last year's report for individual sources, as well as the executive summary, introduction, and reference sections of this document. TFI offers the following comments on the Draft Inventory. Specific comments are delineated in the sections below. TFI requests that EPA provide a meaningful response to these technical and public comments on the Draft Inventory, so that TFI members can review and understand the Agency's rationale in accepting or rejecting comments. TFI again offers to meet with EPA personnel to discuss concerns and specific comments.*

Commenter: The Fertilizer Institute

Comment: *TFI supports the creation of the Urea Consumption for Non-Agricultural Purposes in the Draft Inventory. The new category reflects a harmonized methodology throughout the Draft Inventory and attributes emissions to categories only when that category generates the emissions in question. TFI again offers to work with EPA on its planned future improvements to the urea consumption for non-agricultural purposes source category, by assisting in obtaining data on* *how much urea is consumed for specific applications in the United States and whether C is released to the environment fully during each application.*

- *In Section 4.6 of the Draft Inventory, EPA includes a new, distinct category for Urea Consumption for Non-Agricultural Purposes. See Draft Inventory, pp. 4-20 – 4-22. In this subsection, EPA quantifies the CO2 generated during ammonia production and captured in the production of urea.*
- *TFI supports the inclusion of this category. As delineated in past years' comments, TFI feels that a separate category eliminates a major inconsistency in the Draft Inventory—specifically, that the ammonia/urea production category was one of the few categories in which CO2 emissions resulting from subsequent use of a material were attributed back to the manufacturing industry. TFI had previously stated that release of CO2 during urea consumption is dependent upon the specific use of urea and that there is no basis for assuming that consumed urea releases all CO2 to the environment. Further, because some portion of the non-fertilizer use of urea is attributable to source categories that have greenhouse gas emissions estimated in the Draft Inventory, greenhouse gas emissions may be overstated because of double-counting.*
- *Attributing CO2 emissions associated with urea production to ammonia/urea manufacturers is significant. According to the Draft Inventory, a separate category for non-agricultural uses of urea results in a 27 percent decrease in CO2 emissions identified by EPA for the ammonia/urea production category. Draft Inventory, p. 4-20. The CO2 used to manufacture urea is driven by stoichiometric rates and cannot be manipulated to decrease CO2 emissions attributable to ammonia production. Thus, the separate category for non-agricultural uses treats CO2 content of urea in a manner similar to other non-energy uses of carbon sources–that is, these emissions are attributed to the manufacturing sector emitting the CO2 during urea processing or use.*

Commenter: The Fertilizer Institute

Comment: *TFI requests that EPA provide affected and interested parties with a plan for harmonization of the Draft Inventory and the GHGRP, which results in a single database of GHG emissions in the U.S. based on empirical data. This database should be consistent with IPCC procedures, including the allocation of ammonia CO2 in the production of urea.*

Estimates for the remaining 10-15% of total GHG emissions for sources not included in the GHGRP can be used in the database unless or until the emissions data from these sources are also empirically quantified.

Throughout the Draft Inventory, EPA indicates in the Planned Improvements section that the Agency will use greenhouse gas emissions data from the EPA Greenhouse Gas Reporting Program (GHGRP) as a basis for improving emissions calculations. The EPA states that the Agency will assess how this data could be used to improve the overall method for calculating emissions and specifically assessing data to update emission factors and other calculations (see for example Ammonia Production section at 4-20).

TFI questions the efficacy of this methodology as opposed to harmonizing data to create a single report characterizing domestic greenhouse gas emissions. Now that empirical greenhouse gas emissions data are available in the GHGRP that cover 85-90% of the total greenhouse gas emissions in the U.S., by EPA's own estimate, TFI questions the value of EPA maintaining two separate databases–the Draft Inventory and the GHGRP– to describe these emissions from various sources. TFI believes it makes more sense to harmonize these data and methodologies so that EPA's annual inventory of greenhouse gas emissions in the U.S. is based on actual data, to the extent possible, that are consistent with the Intergovernmental Panel on Climate Change (IPCC) guidance, including the correct allocation of ammonia CO2 used in the production of urea that is subsequently consumed off-site from the ammonia and urea production facility. The use of qualifying disclaimers, such as Some CO2 is captured and is therefore not emitted as found on the GHGRP website, is inconsistent and insufficient in explaining that not all of the CO2 generated during the production of ammonia is emitted from the facility.

Commenter: Mary Power Giacoletti of San Luis Obispo County

Comment: *San Luis Obispo County recently approved a Climate Action Plan to reduce greenhouse gas emissions. The biggest flaw in that plan was the omission of the critical role that black carbon (soot) plays in the climate/pollution dynamic. NASA has listed soot as a top-priority pollutant in that regard. Tackling the enormous global problem of soot first, rather than last, should be an integral part of the EPA's Report. Unfortunately, the issue is as glossed over as it was in our county plan.*

- *There is a passing mention on page 24 (Energy) to difficulties calculating emissions from wood combustion (i.e. fireplaces and wood stoves.) San Luis Obispo County is not atypical. Our greatest, and most dangerous pollution is in the form of soot from mostly antiquated residential fireplaces and wood stoves. We have an additional and fast-growing wood-burning barbecue source, both residential and commercial, along with a similar trend in conversational fire pits. The end result is a very high level of soot and a high rate of disease (heart, cancer, asthma). Why there is difficultyon both the county and the federal level to not only calculate emissions but to reduce them is a bit of a mystery. Soot is a low-hanging fruit in the overall plan to modify global warming. I* *would suggest that the EPA Inventory Report give greater emphasis to the black carbon problem.*

- *On page 19 (Energy): In general the carbon content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. I believe that a report on the hierarchy of pollutants lists green waste as the highest, followed by dung, followed by wood - then followed by coal, etc.*
- *For the sake of the planet and the basic human right to breathe, I urge the EPA to address the pervasive problem of wood-burning soot in an overall climate/pollution plan.*

Commenter: America's Natural Gas Alliance

Comment: *The change in the methodology for estimating emissions from natural gas well liquid unloading (also referred to as cleanups) account for the majority of the increase in emissions from natural gas production from the 2010 Draft Inventory to the 2011 and 2012 Draft Inventories. The revised methodology contains a critical flaw in its failure to include emission reductions from the use of artificial lift systems, such as plunger lifts, that are not reported under the Natural Gas STAR Program because they are part of economic recovery as opposed to an emissions reduction technology.*

Artificial lift systems provide substantial reductions in emissions from liquid unloading, but as Staff acknowledged in its July 2011 webcast with stakeholders, EPA significantly underestimates their use in the inventory. Generally, venting of gas during lift cycles is an old practice that has been largely replaced with methods that capture the gas. In addition to plunger lift systems – which can eliminate emissions entirely – there are a number of technologies used to reduce or eliminate venting from unloading, including but not limited to:

- *Velocity string (install smaller diameter tubing to increase the velocity);*
- *Compression (reduce tubing pressure);*
- *Pumps;*
- *Gaslift (added gas to boost flow above critical);*
- *Foaming (soap sticks, back side soap injection, cap string);*
- *Injection systems (inject water below packer); and*
- *Venting/Stop Clocking/Equalizing (temporary methods that are used in some cases).*

The omission of emission reductions from the application of these practices results in a worst-case scenario approach that is not appropriate for an emissions inventory and dramatically overestimates the emissions from natural gas production.

EPA's new methodology raises concerns. EPA appears to have developed the methodology based on two sources.5 The first source, an EPA/Natural Gas STAR report Lessons Learned:

Installing Plunger Lift Systems in Natural Gas Wells6, provides an equation for estimating the volume of gas vented during a blowdown:

As noted by El Paso Corporation in their comments on the 2011 Draft Inventory, EPA has not indicated whether the equation or the results were adjusted for the purposes of the Draft Inventory or provided the data, or average characteristics, that EPA used in the equation. EPA states that it used production and permit data obtained from HPDI in October 2009 for at least part of the data to run the equation. HPDI supplied information on well depth, shut-in pressure, well counts and well production data. However, more detail on the data actually used, particularly the data used to calculate shut-in pressure (which is needed to ensure that EPA focused on low pressure wells where liquid unloading is more prevalent), is necessary to adequately evaluate the methodology and results.

The equation only provides the volume vented for each blowdown. To complete the inventory, EPA needs to know how many wells required cleanups (Wc) and how many blowdowns are required annually at those wells (BDa) so that:

*U.S. Methane Emissions from Cleanups = Wc*BDa*Vv*0.7887*

Annex 3, page A-150.

http://epa.gov/gasstar/documents/ll_plungerlift.pdf

The total volume of natural gas must be adjusted to differentiate methane from other gases. EPA assumes that 78.8 percent of vented gas is methane. Annex 3, A-151.

The documentation for the inventory does not indicate what data were used to estimate Wc or BDa. While the HPDI data would have provided the total number of wells, it is unlikely that HPDI's production data would have provided information on which wells perform cleanups and the number of blowdowns performed each year at those wells.

EPA has recently estimated these two variables. Appendix B of the Technical Support Document (TSD) developed in support of Subpart W of the Mandatory Greenhouse Gas Reporting Rule uses data from a 1992 survey conducted by the Gas Research Institute (GRI) to estimate that 41.3 percent of conventional wells require cleanups. The 1992 survey was of 25 well sites.

To determine the average number of blowdowns at each well, the TSD uses a simple average of blowdowns per well based on publicly available data from two Natural Gas STAR partners:

- *BP recovered 4 Bcf of emissions using plunger lifts with automation to optimize plunger cycles on 2,200 wells in the San Juan basin.8 Using the equation for blowdown emissions, EPA determined that 51 blowdowns per well would be required to match the reported 4 Bcf of emissions.*

- *ExxonMobil reported it recovered 12 MMcf using plunger lifts on 19 wells in Big Piney.9 EPA used the blowdown emissions equation to estimate about 11 blowdowns per well to match the 12 MMcf of emissions.*

ANGA notes that the blowdown estimate is based on two isolated data points and does not appear to account for well-specific variables, such as differences in well depth (shallow wells such as those in the San Juan Basin require more blowdowns than deep wells), that drive the number of necessary blowdowns. If EPA has developed additional assumptions for determining the number of blowdowns, including well-specific data, it should disclose them and provide an opportunity for comment.

To address these issues, ANGA supports the alternative approach detailed in El Paso Corporation's comments that begins with estimating emissions per event using approaches similar to those proposed in the Mandatory Reporting Rule and then applying the emissions estimate to wells that (a) use cleanups and (b) do not use artificial lift of any kind. As discussed in the next section, the emissions should also be adjusted for reasonable estimates on the amount of gas that is flared instead of vented.

Emissions from Unconventional Well Completions and Workovers

In the 2011 GHG Inventory, EPA added two new categories: unconventional gas well completions and unconventional gas well workovers.10 The addition of these two categories accounted for 28 percent of the increase in estimated 2008 emissions from natural gas field production from the 2010 to the 2011 GHG Inventory.

The Technical Support Document (TSD) prepared in support of Subpart W outlines the approach EPA used to develop the emissions factor. The Subpart W TSD uses four data points to develop an estimate of emissions from completions. The first presentation, dated September 21, 2004 and given by EPA at a Producer's Technology Transfer Workshop sponsored by the American Petroleum Institute, ExxonMobil Production Company, and EPA includes three of the data points11:

- *The presentation cites an EIA estimate of 45 Bcf of methane emissions from completions and workovers in 2002. In the TSD, EPA uses API's Basic Petroleum Handbook to estimate that there were 5,188 conventional wells drilled in 2002 and 7,783 unconventional wells. Using the default emissions factor from EPA's Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 for the conventional wells (which EPA reports in the TSD is 49,570 scf/well-year), EPA concludes that conventional wells were responsible for 0.3 Bcf of the 45 Bcf of emissions from completions and workovers in 2002. EPA then divided the remaining 44.7 Bcf by the unconventional wells to arrive at a rounded estimate of 6,000 Mcf/completion.*
- *The second data point in the same presentation was a Natural Gas STAR case study from Devon Energy showing that they implemented reduced emission completion. These terms*

are not commonly used in industry. For clarity and consistency, EPA should use the same terminology it used in Subpart W and in the proposed Oil & Gas NSPS/NESHAP – with and without hydraulic fracturing.

- *The third data point in the same presentation was a case study of a project at three wells in a coal bed methane project. The project captured 2,000 Mcf or about 700 Mcf/completion in EPA's rounded estimate.*
- *The presentation, by the Williams Companies, estimated the natural gas captured from a project to reduce methane emissions from completions at an unconventional natural gas project. EPA's rounded estimate of recovered gas was 20,000 Mcf/completion.*

The Subpart W TSD took these four estimates and calculated a simple average ((6,000 + 10,000 + 700 + 20,000)/4) to arrive at an emissions estimate of 9,175 Mcf/completion for unconventional wells. EPA applied the same number to workovers. Since EPA does not have alternative data, it uses the same factor for recompletions as it does for initial completions.

EPA used the same analysis to estimate emissions from hydraulically fractured well completions and recompletions in the proposed O&G NSPS/NESHAP.13 As noted in ANGA's comments to EPA regarding the O&G NSPS/NESHAP,14 not only is the emission factor based on only four data points with the high end nearly 30 times higher than the low end, a fatal flaw in itself, but none of the data points were purported to be representative estimates of emissions from completions or recompletions. Rather, they are case studies from a voluntary EPA program aimed at reducing emissions (Natural Gas STAR) and, as such, they are reporting the results of a handful of projects in the field. They are not based on standardized and audited protocols. Moreover, case studies, by their nature, are typically based on projects that will provide statistically significant results and are not based on the average project. Since in this context, the best projects are the ones that capture the greatest amount of emissions, using those captured emissions to estimate average uncontrolled emissions can lead to grossly inaccurate results.

The bottom line is that EPA has the methodology backwards. The Agency should evaluate the volumes that are emitted from non-green completion activities rather than rely on green completion volumes from a voluntary program that was never intended to provide inventory-grade information to the Agency. ANGA urges EPA to work with operators to better understand how actual emissions from hydraulically fractured well completions and recompletions compare with their current estimates. We believe that the Agency would find that emissions are significantly less than EPA estimates. For example, eight ANGA member companies recently provided data to URS Corporation on 2011 well completions. As detailed in a memorandum prepared by URS Corporation for ANGA and submitted to EPA as part of the O&G NSPS/NESHAP and updated with a submission to EPA on January 19, 2011, 93% of 1475 wells in the consolidated dataset were green completed, compared to 15% assumed by EPA. Of those wells not completed using REC equipment, only 46% were vented, and the rest were pit flared. Using EPA's recommended method for calculating emissions from gas well completions (Equation W-11B as listed in the proposed September 9, 2011 revisions to Subpart W of the

MRR), URS found that natural gas emissions from vented wells were only about 8% of EPA's estimated emissions on a per well basis (765 Mcf of gas compared to 9175 Mcf used by EPA). The updated memorandum is attached.

In addition, we note that even the data point that was not based on green completions (the EIA data used for the 6,000 Mcf/completion estimate) raises serious concerns. First, when backing out emissions attributable to conventional well completions and workovers, the TSD uses the old emission factors for conventional wells and assumes the rest is attributable to unconventional wells. The TSD provides no support in the EIA data for this assumption, nor does EPA explain why it uses an old emissions factor that has been revised in the TSD.15 Based on the lack of data, a more reasonable approach would be to adjust based on the fraction of conventional wells – 40 percent. Making this adjustment,conventional wells would be responsible for 18 Bcf, leaving 27 Bcf attributable to unconventional wells. The TSD then applies all remaining emissions to completions, instead of first adjusting for workovers (the 45 Bcf applies to completions and workovers, but the TSD emissions estimate is for completions only). For example, according to data in the TSD, there were 13,403 unconventional well completions and workovers in 2007, and of these, 31 percent were workovers. After this adjustment, 18.6 Bcf are attributable to unconventional well completions. Dividing that by the number of completed wells yields an average emission rate of approximately 2,350/Mcf per completion – substantially less than half the estimate in the TSD. This provides further support to the conclusion that EPA's methodology significantly overestimates emissions from unconventional well completions and workovers.

Given the number of uncertainties with respect to the accuracy of the calculations of estimated emissions from well completions and recompletions, including the underlying data and assumptions, and the fact that EPA has not followed its own procedures in development of emissions factors for these activities,16 ANGA believes that it is inappropriate for EPA to continue to use these emissions factors. EPA must develop accurate, peer-reviewed emissions estimations that are based on valid data, assumptions and calculations. ANGA stands ready to continue to work with EPA to develop valid emission factors and estimates for well completions and recompletions that can serve as the basis for more accurate emissions estimates.

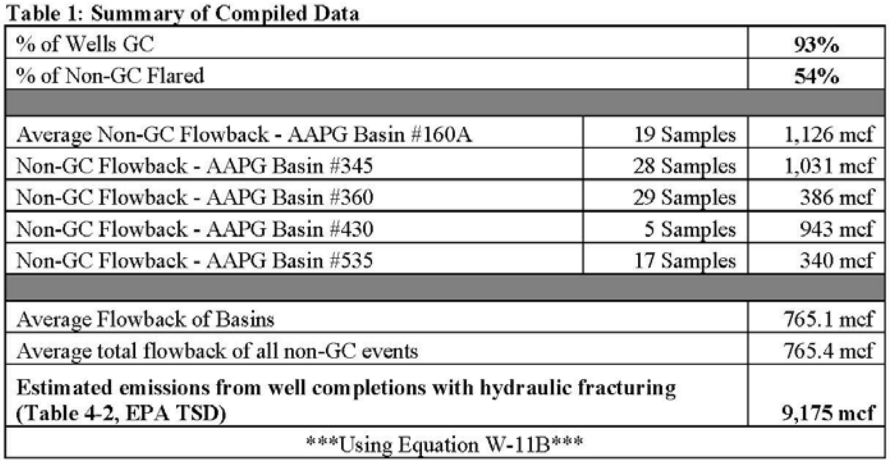
Conclusion

ANGA understands EPA's desire to accurately estimate emissions from unconventional wells, but the operative word must be accurately. Given the magnitude of the changes and their impact on the national inventory, the underlying data and assumptions must be rigorous and well supported. That is not the case for either natural gas well cleanups or unconventional well completions and workovers.

Last year, we noted that if the significant flaws in the methodologies were not corrected, the resulting emissions estimates will provide inaccurate information to those who rely on the *national inventory for analysis and decisions, including regulatory action, and undermine the purpose and credibility of the national inventory program. This warning has borne out as a number of researchers have used the 2011 GHG Inventory as the basis for lifecycle analyses of natural gas without acknowledging the clear shortcomings in EPA's methodology. In addition, there are several ongoing federal and state regulatory initiatives that will ultimately rely, in some part, on emission estimates as set forth in the inventory. In light of the serious concerns with respect to the methodology and the quality of the data generated for the Draft Inventory, we ask that either EPA update the emissions estimates for natural gas cleanups and unconventional well completions and workovers or exclude them from the inventory until more robust data and methodologies have been developed and subjected to public comment. At a minimum, EPA should include a statement at the beginning of Chapter 3 of the inventory, and in a footnote to every table and figure that includes emissions from Natural Gas Systems, indicating that it has received information and data related to National Gas System emissions estimates that indicates that the methodology needs to be revised, that the Agency is in the process of revising its methodology, and that until such time as the methodology has been revised and implemented and new emissions estimates based on the revised methodology are available, the emissions estimates in the inventory should not be relied upon or otherwise used as the basis for any analysis or regulatory action.*

ATTACHMENTS

Table 1: Summary of Compiled Data



% of Wells GC		**93%**
% of Non-GC Flared		**54%**
Average Non-GC Flowback - AAPG Basin #160A	19 Samples	1,126 mcf
Non-GC Flowback - AAPG Basin #345	28 Samples	1,031 mcf
Non-GC Flowback - AAPG Basin #360	29 Samples	386 mcf
Non-GC Flowback - AAPG Basin #430	5 Samples	943 mcf
Non-GC Flowback - AAPG Basin #535	17 Samples	340 mcf
Average Flowback of Basins		765.1 mcf
Average total flowback of all non-GC events		765.4 mcf
Estimated emissions from well completions with hydraulic fracturing (Table 4-2, EPA TSD)		**9,175 mcf**
Using Equation W-11B		

Figure 2: Distribution of Single-Event Flowback Volumes (Non-Green Completions only)

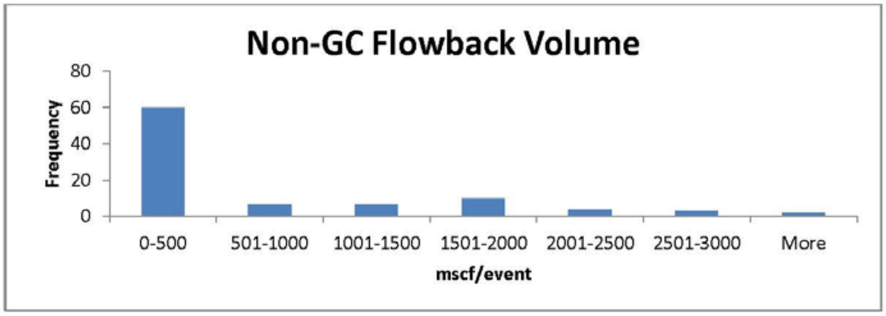


Figure 3: Distribution of Casing Pressures (Non-Green Completions only)

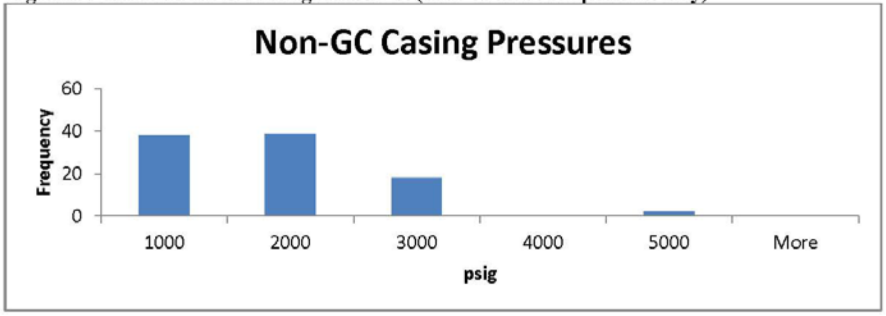


Figure 4: Distribution of Green Completion Durations

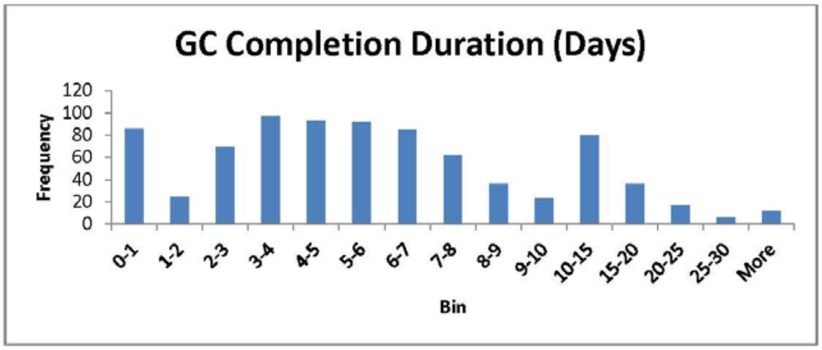


Figure 5: AAPG Basins Represented in Survey Sample (Non-GC Only)

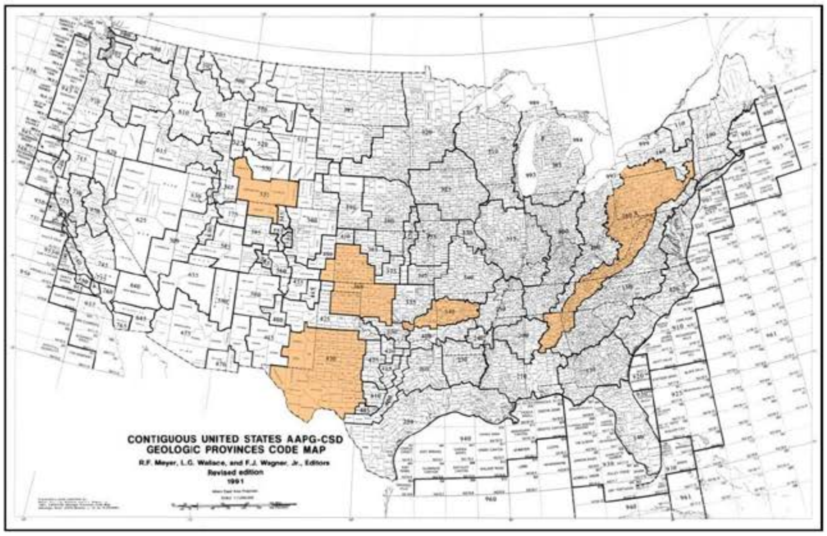


Figure 6: Location of Major Shale Plays in Continental US

Source:
http://www.slb.com/services/industry_challenges/~/media/Files/industry_challenges/unconventional_gas/other/shale_plays_lower_48.ashx

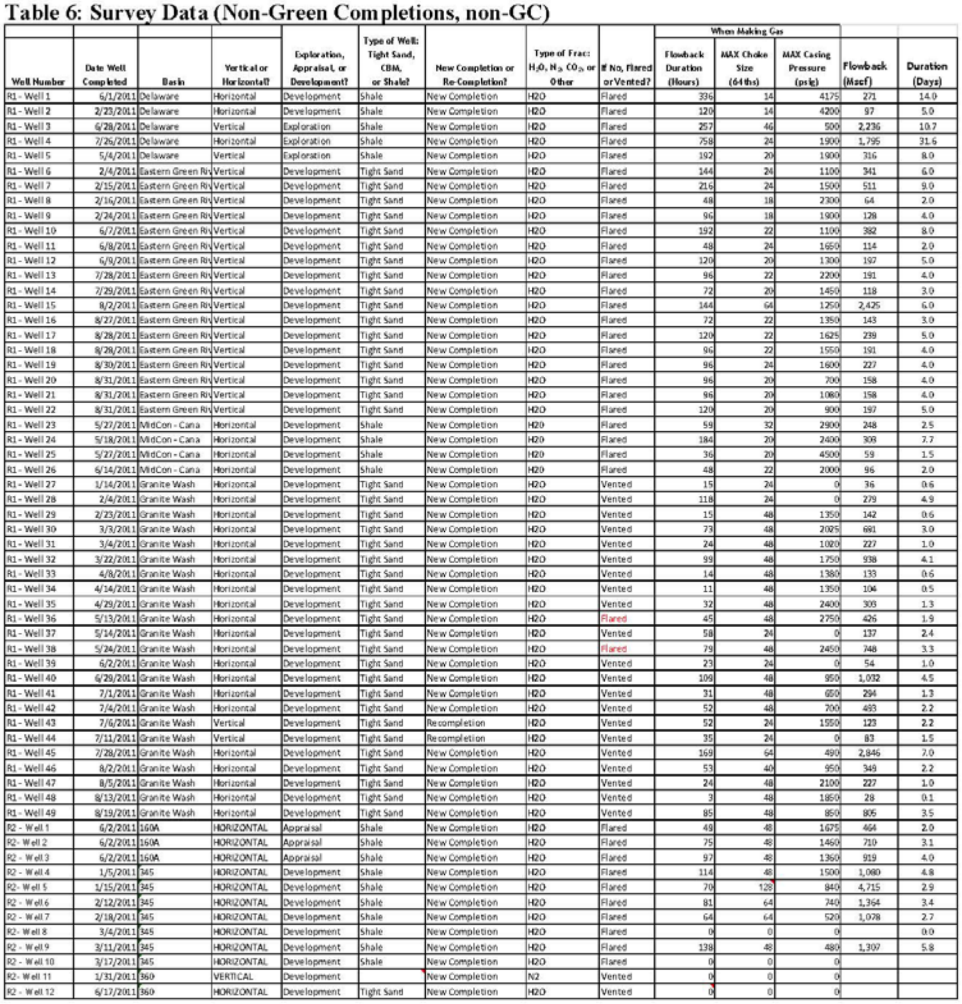
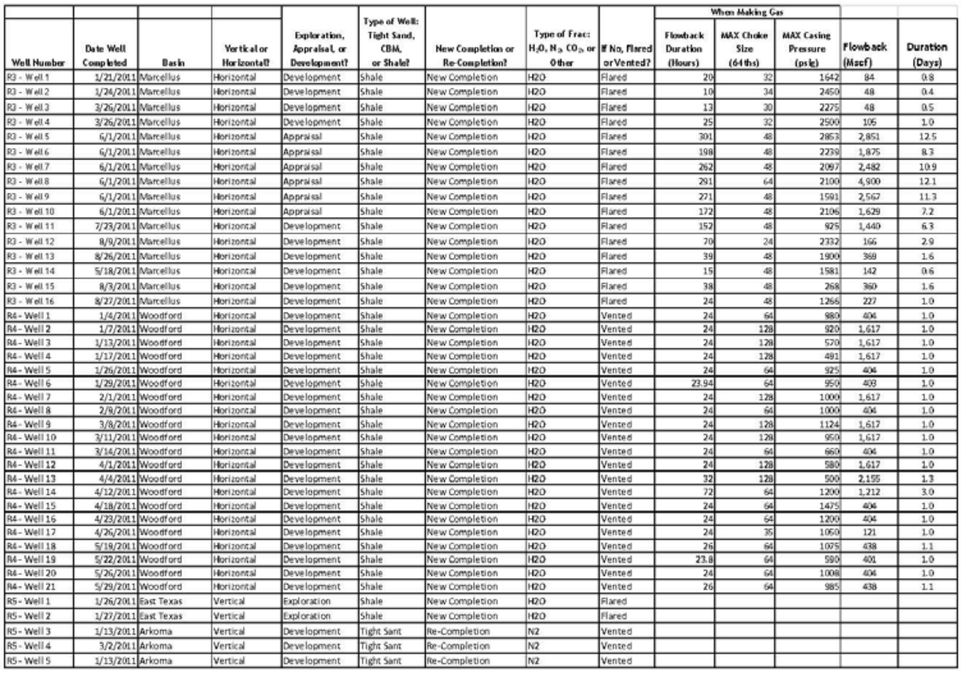


Table 6: Survey Data (Non-Green Completions, non-GC)

									When Making Gas				
Well Number	Date Well Completed	Basin	Vertical or Horizontal?	Exploration, Appraisal, or Development?	Type of Well: Tight Sand, CBM, or Shale?	New Completion or Re-Completion?	Type of Frac: H_2O, N_2, CO_2, or Other	If No, Flared or Vented?	Flowback Duration (Hours)	MAX Choke Size (64ths)	MAX Casing Pressure (psig)	Flowback (Mscf)	Duration (Days)
R1 - Well 1	6/1/2011	Delaware	Horizontal	Development	Shale	New Completion	H2O	Flared	336	14	4175	271	14.0
R1 - Well 2	2/23/2011	Delaware	Horizontal	Development	Shale	New Completion	H2O	Flared	120	14	4200	97	5.0
R1 - Well 3	6/28/2011	Delaware	Vertical	Exploration	Shale	New Completion	H2O	Flared	257	46	500	2,236	10.7
R1 - Well 4	7/26/2011	Delaware	Horizontal	Exploration	Shale	New Completion	H2O	Flared	758	24	1900	1,795	31.6
R1 - Well 5	5/4/2011	Delaware	Vertical	Exploration	Shale	New Completion	H2O	Flared	192	20	1900	316	8.0
R1 - Well 6	2/4/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	144	24	1100	341	6.0
R1 - Well 7	2/15/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	216	24	1500	511	9.0
R1 - Well 8	2/16/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	48	18	2300	64	2.0
R1 - Well 9	2/24/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	96	18	1900	128	4.0
R1 - Well 10	6/7/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	192	22	1100	382	8.0
R1 - Well 11	6/8/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	48	24	1650	114	2.0
R1 - Well 12	6/9/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	120	20	1300	197	5.0
R1 - Well 13	7/28/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	96	22	2200	191	4.0
R1 - Well 14	7/29/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	72	20	1450	118	3.0
R1 - Well 15	8/2/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	144	64	1250	2,425	6.0
R1 - Well 16	8/27/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	72	22	1350	143	3.0
R1 - Well 17	8/28/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	120	22	1625	239	5.0
R1 - Well 18	8/28/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	96	22	1550	191	4.0
R1 - Well 19	8/30/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	96	24	1600	227	4.0
R1 - Well 20	8/31/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	96	20	700	158	4.0
R1 - Well 21	8/31/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	96	20	1080	158	4.0
R1 - Well 22	8/31/2011	Eastern Green Ri	Vertical	Development	Tight Sand	New Completion	H2O	Flared	120	20	900	197	5.0
R1 - Well 23	5/27/2011	MidCon - Cana	Horizontal	Development	Shale	New Completion	H20	Flared	59	32	2900	248	2.5
R1 - Well 24	5/18/2011	MidCon - Cana	Horizontal	Development	Shale	New Completion	H20	Flared	184	20	2400	308	7.7
R1 - Well 25	5/27/2011	MidCon - Cana	Horizontal	Development	Shale	New Completion	H20	Flared	36	20	4500	59	1.5
R1 - Well 26	6/14/2011	MidCon - Cana	Horizontal	Development	Shale	New Completion	H20	Flared	48	22	2000	96	2.0
R1 - Well 27	1/14/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	15	24	0	36	0.6
R1 - Well 28	2/4/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	118	24	0	279	4.9
R1 - Well 29	2/23/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	15	48	1350	142	0.6
R1 - Well 30	3/3/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	73	48	2025	681	3.0
R1 - Well 31	3/4/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	24	48	1020	227	1.0
R1 - Well 32	3/22/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	99	48	1750	938	4.1
R1 - Well 33	4/8/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	14	48	1380	133	0.6
R1 - Well 34	4/14/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	11	48	1350	104	0.5
R1 - Well 35	4/29/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	32	48	2400	303	1.3
R1 - Well 36	5/13/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Flared	45	48	2750	426	1.9
R1 - Well 37	5/14/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	58	24	0	137	2.4
R1 - Well 38	5/24/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Flared	79	48	2450	748	3.3
R1 - Well 39	6/2/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	23	24	0	54	1.0
R1 - Well 40	6/29/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	109	48	950	1,032	4.5
R1 - Well 41	7/1/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	31	48	650	294	1.3
R1 - Well 42	7/4/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	52	48	700	493	2.2
R1 - Well 43	7/6/2011	Granite Wash	Vertical	Development	Tight Sand	Recompletion	H2O	Vented	52	24	1550	123	2.2
R1 - Well 44	7/11/2011	Granite Wash	Vertical	Development	Tight Sand	Recompletion	H2O	Vented	35	24	0	83	1.5
R1 - Well 45	7/28/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	169	64	490	2,846	7.0
R1 - Well 46	8/2/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	53	40	950	349	2.2
R1 - Well 47	8/5/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	24	48	2100	227	1.0
R1 - Well 48	8/13/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	3	48	1850	28	0.1
R1 - Well 49	8/19/2011	Granite Wash	Horizontal	Development	Tight Sand	New Completion	H2O	Vented	85	48	850	805	3.5
R2 - Well 1	6/2/2011	160A	HORIZONTAL	Appraisal	Shale	New Completion	H2O	Flared	49	48	1675	464	2.0
R2- Well 2	6/2/2011	160A	HORIZONTAL	Appraisal	Shale	New Completion	H2O	Flared	75	48	1460	710	3.1
R2 - Well 3	6/2/2011	160A	HORIZONTAL	Appraisal	Shale	New Completion	H2O	Flared	97	48	1360	919	4.0
R2 - Well 4	1/5/2011	345	HORIZONTAL	Development	Shale	New Completion	H2O	Flared	114	48	1500	1,080	4.8
R2- Well 5	1/15/2011	345	HORIZONTAL	Development	Shale	New Completion	H2O	Flared	70	128	840	4,715	2.9
R2 - Well 6	2/12/2011	345	HORIZONTAL	Development	Shale	New Completion	H2O	Flared	81	64	740	1,364	3.4
R2 - Well 7	2/18/2011	345	HORIZONTAL	Development	Shale	New Completion	H2O	Flared	64	64	520	1,078	2.7
R2- Well 8	3/4/2011	345	HORIZONTAL	Development	Shale	New Completion	H2O	Flared	0	0	0		0.0
R2 - Well 9	3/11/2011	345	HORIZONTAL	Development	Shale	New Completion	H2O	Flared	138	48	480	1,307	5.8
R2 - Well 10	3/17/2011	345	HORIZONTAL	Development	Shale	New Completion	H2O	Flared	0	0	0		
R2- Well 11	1/31/2011	360	VERTICAL	Development		New Completion	N2	Vented	0	0	0		
R2 - Well 12	6/17/2011	360	HORIZONTAL	Development	Tight Sand	New Completion	H2O	Vented	0	0	0		

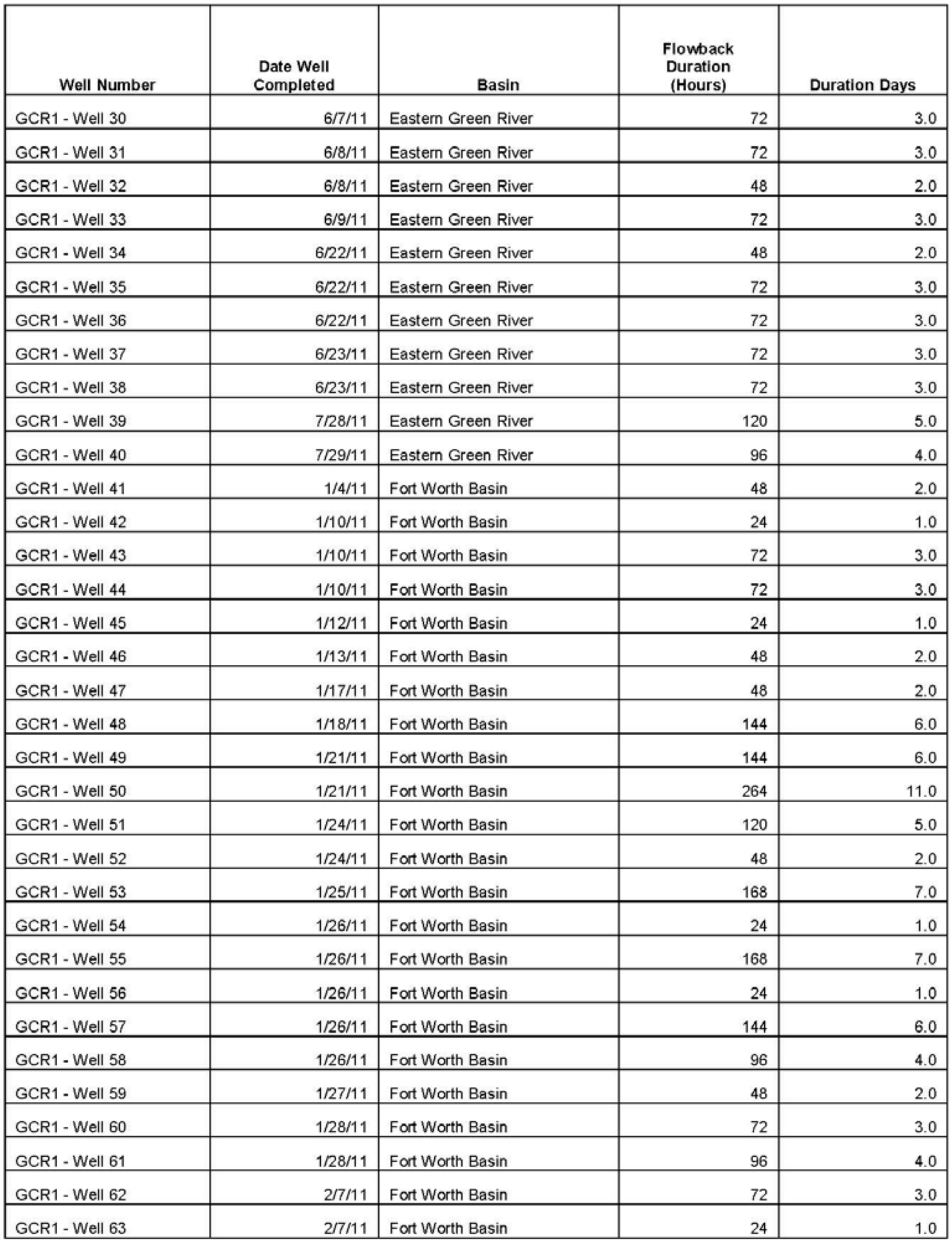
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 98	5/3/11	Fort Worth Basin	144	6.0
GCR1 - Well 99	5/3/11	Fort Worth Basin	696	29.0
GCR1 - Well 100	5/15/11	Fort Worth Basin	120	5.0
GCR1 - Well 101	5/21/11	Fort Worth Basin	48	2.0
GCR1 - Well 102	5/26/11	Fort Worth Basin	144	6.0
GCR1 - Well 103	5/26/11	Fort Worth Basin	120	5.0
GCR1 - Well 104	5/27/11	Fort Worth Basin	120	5.0
GCR1 - Well 105	5/28/11	Fort Worth Basin	72	3.0
GCR1 - Well 106	5/28/11	Fort Worth Basin	96	4.0
GCR1 - Well 107	5/31/11	Fort Worth Basin	48	2.0
GCR1 - Well 108	5/31/11	Fort Worth Basin	48	2.0
GCR1 - Well 109	6/2/11	Fort Worth Basin	288	12.0
GCR1 - Well 110	6/2/11	Fort Worth Basin	48	2.0
GCR1 - Well 111	6/9/11	Fort Worth Basin	24	1.0
GCR1 - Well 112	6/18/11	Fort Worth Basin	216	9.0
GCR1 - Well 113	6/18/11	Fort Worth Basin	120	5.0
GCR1 - Well 114	6/23/11	Fort Worth Basin	96	4.0
GCR1 - Well 115	6/23/11	Fort Worth Basin	48	2.0
GCR1 - Well 116	6/24/11	Fort Worth Basin	24	1.0
GCR1 - Well 117	6/25/11	Fort Worth Basin	24	1.0
GCR1 - Well 118	6/28/11	Fort Worth Basin	48	2.0
GCR1 - Well 119	7/11/11	Fort Worth Basin	96	4.0
GCR1 - Well 120	7/19/11	Fort Worth Basin	264	11.0
GCR1 - Well 121	8/1/11	Fort Worth Basin	240	10.0
GCR1 - Well 122	8/1/11	Fort Worth Basin	96	4.0
GCR1 - Well 123	8/1/11	Fort Worth Basin	96	4.0
GCR1 - Well 124	8/1/11	Fort Worth Basin	96	4.0
GCR1 - Well 125	8/1/11	Fort Worth Basin	96	4.0
GCR1 - Well 126	8/2/11	Fort Worth Basin	216	9.0
GCR1 - Well 127	8/9/11	Fort Worth Basin	24	1.0
GCR1 - Well 128	8/15/11	Fort Worth Basin	168	7.0
GCR1 - Well 129	8/17/11	Fort Worth Basin	120	5.0
GCR1 - Well 130	8/19/11	Fort Worth Basin	264	11.0
GCR1 - Well 131	8/19/11	Fort Worth Basin	168	7.0



									When Making Gas				
Well Number	Date Well Completed	Basin	Vertical or Horizontal?	Exploration, Appraisal, or Development?	Type of Well: Tight Sand, CBM, or Shale?	New Completion or Re-Completion?	Type of Frac: H_2O, N_2, CO_2, or Other	If No, Flared or Vented?	Flowback Duration (Hours)	MAX Choke Size (64ths)	MAX Casing Pressure (psig)	Flowback (Mscf)	Duration (Days)
R3 - Well 1	1/21/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	20	32	1642	84	0.8
R3 - Well 2	1/24/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	10	34	2450	48	0.4
R3 - Well 3	3/26/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	13	30	2275	48	0.5
R3 - Well 4	3/26/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	25	32	2500	105	1.0
R3 - Well 5	6/1/2011	Marcellus	Horizontal	Appraisal	Shale	New Completion	H2O	Flared	301	48	2853	2,851	12.5
R3 - Well 6	6/1/2011	Marcellus	Horizontal	Appraisal	Shale	New Completion	H2O	Flared	198	48	2239	1,875	8.3
R3 - Well 7	6/1/2011	Marcellus	Horizontal	Appraisal	Shale	New Completion	H2O	Flared	262	48	2097	2,482	10.9
R3 - Well 8	6/1/2011	Marcellus	Horizontal	Appraisal	Shale	New Completion	H2O	Flared	291	64	2100	4,900	12.1
R3 - Well 9	6/1/2011	Marcellus	Horizontal	Appraisal	Shale	New Completion	H2O	Flared	271	48	1591	2,567	11.3
R3 - Well 10	6/1/2011	Marcellus	Horizontal	Appraisal	Shale	New Completion	H2O	Flared	172	48	2106	1,629	7.2
R3 - Well 11	7/23/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	152	48	925	1,440	6.3
R3 - Well 12	8/9/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	70	24	2332	166	2.9
R3 - Well 13	8/26/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	39	48	1900	369	1.6
R3 - Well 14	5/18/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	15	48	1581	142	0.6
R3 - Well 15	8/3/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	38	48	268	360	1.6
R3 - Well 16	8/27/2011	Marcellus	Horizontal	Development	Shale	New Completion	H2O	Flared	24	48	1266	227	1.0
R4 - Well 1	1/4/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	64	980	404	1.0
R4 - Well 2	1/7/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	128	920	1,617	1.0
R4 - Well 3	1/13/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	128	570	1,617	1.0
R4 - Well 4	1/17/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	128	491	1,617	1.0
R4 - Well 5	1/26/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	64	925	404	1.0
R4 - Well 6	1/29/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	23.94	64	950	403	1.0
R4 - Well 7	2/1/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	128	1000	1,617	1.0
R4 - Well 8	2/9/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	64	1000	404	1.0
R4 - Well 9	3/8/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	128	1124	1,617	1.0
R4 - Well 10	3/11/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	128	950	1,617	1.0
R4 - Well 11	3/14/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	64	660	404	1.0
R4 - Well 12	4/1/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	128	580	1,617	1.0
R4 - Well 13	4/4/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	32	128	500	2,155	1.3
R4 - Well 14	4/12/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	72	64	1200	1,212	3.0
R4 - Well 15	4/18/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	64	1475	404	1.0
R4 - Well 16	4/23/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	64	1200	404	1.0
R4 - Well 17	4/26/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	35	1060	121	1.0
R4 - Well 18	5/19/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	26	64	1075	438	1.1
R4 - Well 19	5/22/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	23.8	64	590	401	1.0
R4 - Well 20	5/26/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	24	64	1008	404	1.0
R4 - Well 21	5/29/2011	Woodford	Horizontal	Development	Shale	New Completion	H2O	Vented	26	64	985	438	1.1
R5 - Well 1	1/26/2011	East Texas	Vertical	Exploration	Shale	New Completion	H2O	Flared					
R5 - Well 2	1/27/2011	East Texas	Vertical	Exploration	Shale	New Completion	H2O	Flared					
R5 - Well 3	1/13/2011	Arkoma	Vertical	Development	Tight Sant	Re-Completion	N2	Vented					
R5 - Well 4	3/2/2011	Arkoma	Vertical	Development	Tight Sant	Re-Completion	N2	Vented					
R5 - Well 5	1/13/2011	Arkoma	Vertical	Development	Tight Sant	Re-Completion	N2	Vented					

Table 7: Survey Data (Green Completions GC)

Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 1	2/7/11	East Texas	433	18.0
GCR1 - Well 2	5/25/11	East Texas	400	16.7
GCR1 - Well 3	1/11/11	East Texas	422	17.6
GCR1 - Well 4	5/26/11	East Texas	474	19.8
GCR1 - Well 5	3/18/11	East Texas	746	31.1
GCR1 - Well 6	1/3/11	East Texas	634	26.4
GCR1 - Well 7	1/9/11	East Texas	108	4.5
GCR1 - Well 8	4/16/11	East Texas	336	14.0
GCR1 - Well 9	1/9/11	East Texas	120	5.0
GCR1 - Well 10	4/5/11	East Texas	276	11.5
GCR1 - Well 11	3/20/11	East Texas	360	15.0
GCR1 - Well 12	3/19/11	East Texas	324	13.5
GCR1 - Well 13	6/8/11	East Texas	264	11.0
GCR1 - Well 14	2/6/11	East Texas	288	12.0
GCR1 - Well 15	8/5/11	East Texas	420	17.5
GCR1 - Well 16	8/31/11	East Texas	156	6.5
GCR1 - Well 17	8/6/11	East Texas	492	20.5
GCR1 - Well 18	6/1/11	East Texas	288	12.0
GCR1 - Well 19	4/10/11	East Texas	540	22.5
GCR1 - Well 20	3/22/11	East Texas	370	15.4
GCR1 - Well 21	7/1/11	East Texas	216	9.0
GCR1 - Well 22	2/25/11	East Texas	490	20.4
GCR1 - Well 23	2/4/11	Eastern Green River	96	4.0
GCR1 - Well 24	2/15/11	Eastern Green River	72	3.0
GCR1 - Well 25	2/15/11	Eastern Green River	72	3.0
GCR1 - Well 26	2/16/11	Eastern Green River	72	3.0
GCR1 - Well 27	2/17/11	Eastern Green River	96	4.0
GCR1 - Well 28	2/25/11	Eastern Green River	96	4.0
GCR1 - Well 29	2/25/11	Eastern Green River	72	3.0



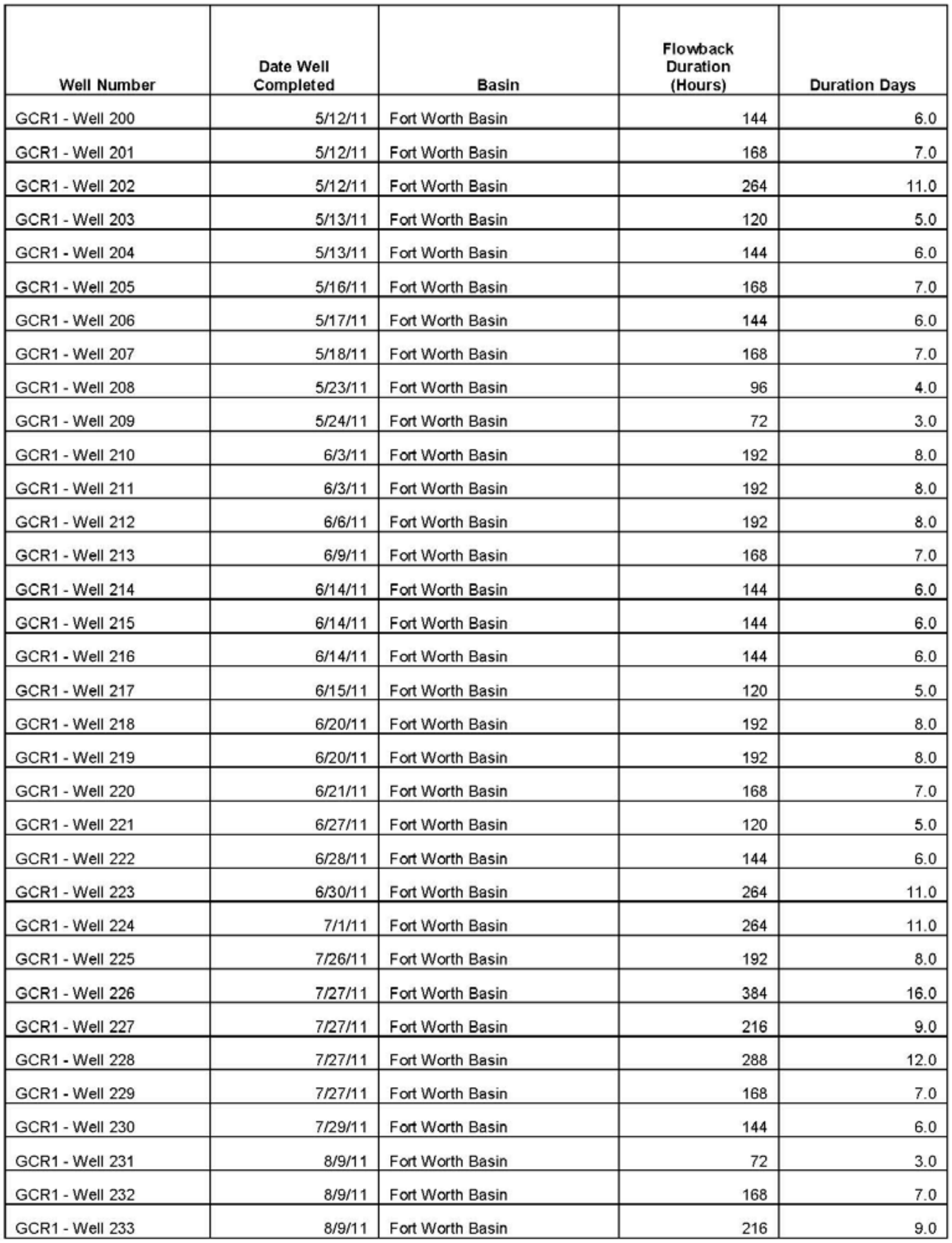
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 30	6/7/11	Eastern Green River	72	3.0
GCR1 - Well 31	6/8/11	Eastern Green River	72	3.0
GCR1 - Well 32	6/8/11	Eastern Green River	48	2.0
GCR1 - Well 33	6/9/11	Eastern Green River	72	3.0
GCR1 - Well 34	6/22/11	Eastern Green River	48	2.0
GCR1 - Well 35	6/22/11	Eastern Green River	72	3.0
GCR1 - Well 36	6/22/11	Eastern Green River	72	3.0
GCR1 - Well 37	6/23/11	Eastern Green River	72	3.0
GCR1 - Well 38	6/23/11	Eastern Green River	72	3.0
GCR1 - Well 39	7/28/11	Eastern Green River	120	5.0
GCR1 - Well 40	7/29/11	Eastern Green River	96	4.0
GCR1 - Well 41	1/4/11	Fort Worth Basin	48	2.0
GCR1 - Well 42	1/10/11	Fort Worth Basin	24	1.0
GCR1 - Well 43	1/10/11	Fort Worth Basin	72	3.0
GCR1 - Well 44	1/10/11	Fort Worth Basin	72	3.0
GCR1 - Well 45	1/12/11	Fort Worth Basin	24	1.0
GCR1 - Well 46	1/13/11	Fort Worth Basin	48	2.0
GCR1 - Well 47	1/17/11	Fort Worth Basin	48	2.0
GCR1 - Well 48	1/18/11	Fort Worth Basin	144	6.0
GCR1 - Well 49	1/21/11	Fort Worth Basin	144	6.0
GCR1 - Well 50	1/21/11	Fort Worth Basin	264	11.0
GCR1 - Well 51	1/24/11	Fort Worth Basin	120	5.0
GCR1 - Well 52	1/24/11	Fort Worth Basin	48	2.0
GCR1 - Well 53	1/25/11	Fort Worth Basin	168	7.0
GCR1 - Well 54	1/26/11	Fort Worth Basin	24	1.0
GCR1 - Well 55	1/26/11	Fort Worth Basin	168	7.0
GCR1 - Well 56	1/26/11	Fort Worth Basin	24	1.0
GCR1 - Well 57	1/26/11	Fort Worth Basin	144	6.0
GCR1 - Well 58	1/26/11	Fort Worth Basin	96	4.0
GCR1 - Well 59	1/27/11	Fort Worth Basin	48	2.0
GCR1 - Well 60	1/28/11	Fort Worth Basin	72	3.0
GCR1 - Well 61	1/28/11	Fort Worth Basin	96	4.0
GCR1 - Well 62	2/7/11	Fort Worth Basin	72	3.0
GCR1 - Well 63	2/7/11	Fort Worth Basin	24	1.0

Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 64	2/9/11	Fort Worth Basin	72	3.0
GCR1 - Well 65	2/12/11	Fort Worth Basin	72	3.0
GCR1 - Well 66	2/12/11	Fort Worth Basin	48	2.0
GCR1 - Well 67	2/12/11	Fort Worth Basin	168	7.0
GCR1 - Well 68	2/13/11	Fort Worth Basin	72	3.0
GCR1 - Well 69	2/15/11	Fort Worth Basin	144	6.0
GCR1 - Well 70	2/16/11	Fort Worth Basin	96	4.0
GCR1 - Well 71	2/16/11	Fort Worth Basin	48	2.0
GCR1 - Well 72	2/17/11	Fort Worth Basin	24	1.0
GCR1 - Well 73	2/18/11	Fort Worth Basin	672	28.0
GCR1 - Well 74	2/18/11	Fort Worth Basin	672	28.0
GCR1 - Well 75	2/25/11	Fort Worth Basin	24	1.0
GCR1 - Well 76	3/18/11	Fort Worth Basin	96	4.0
GCR1 - Well 77	3/18/11	Fort Worth Basin	96	4.0
GCR1 - Well 78	3/26/11	Fort Worth Basin	72	3.0
GCR1 - Well 79	3/26/11	Fort Worth Basin	192	8.0
GCR1 - Well 80	3/26/11	Fort Worth Basin	120	5.0
GCR1 - Well 81	3/28/11	Fort Worth Basin	120	5.0
GCR1 - Well 82	4/1/11	Fort Worth Basin	24	1.0
GCR1 - Well 83	4/2/11	Fort Worth Basin	96	4.0
GCR1 - Well 84	4/3/11	Fort Worth Basin	240	10.0
GCR1 - Well 85	4/3/11	Fort Worth Basin	72	3.0
GCR1 - Well 86	4/4/11	Fort Worth Basin	240	10.0
GCR1 - Well 87	4/6/11	Fort Worth Basin	72	3.0
GCR1 - Well 88	4/9/11	Fort Worth Basin	168	7.0
GCR1 - Well 89	4/10/11	Fort Worth Basin	120	5.0
GCR1 - Well 90	4/11/11	Fort Worth Basin	336	14.0
GCR1 - Well 91	4/11/11	Fort Worth Basin	216	9.0
GCR1 - Well 92	4/13/11	Fort Worth Basin	144	6.0
GCR1 - Well 93	4/26/11	Fort Worth Basin	216	9.0
GCR1 - Well 94	4/26/11	Fort Worth Basin	216	9.0
GCR1 - Well 95	4/29/11	Fort Worth Basin	96	4.0
GCR1 - Well 96	5/1/11	Fort Worth Basin	744	31.0
GCR1 - Well 97	5/2/11	Fort Worth Basin	552	23.0

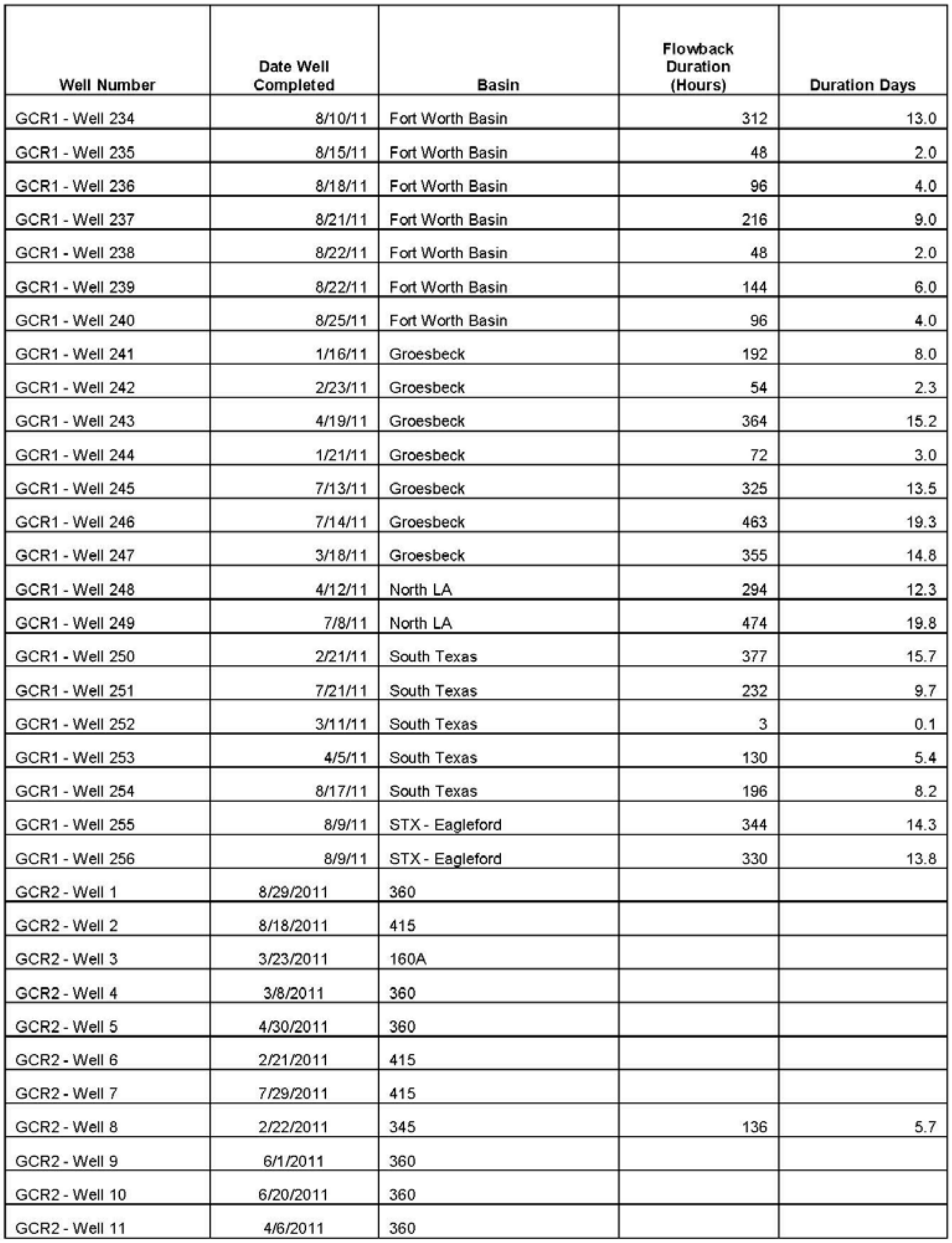
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 98	5/3/11	Fort Worth Basin	144	6.0
GCR1 - Well 99	5/3/11	Fort Worth Basin	696	29.0
GCR1 - Well 100	5/15/11	Fort Worth Basin	120	5.0
GCR1 - Well 101	5/21/11	Fort Worth Basin	48	2.0
GCR1 - Well 102	5/26/11	Fort Worth Basin	144	6.0
GCR1 - Well 103	5/26/11	Fort Worth Basin	120	5.0
GCR1 - Well 104	5/27/11	Fort Worth Basin	120	5.0
GCR1 - Well 105	5/28/11	Fort Worth Basin	72	3.0
GCR1 - Well 106	5/28/11	Fort Worth Basin	96	4.0
GCR1 - Well 107	5/31/11	Fort Worth Basin	48	2.0
GCR1 - Well 108	5/31/11	Fort Worth Basin	48	2.0
GCR1 - Well 109	6/2/11	Fort Worth Basin	288	12.0
GCR1 - Well 110	6/2/11	Fort Worth Basin	48	2.0
GCR1 - Well 111	6/9/11	Fort Worth Basin	24	1.0
GCR1 - Well 112	6/18/11	Fort Worth Basin	216	9.0
GCR1 - Well 113	6/18/11	Fort Worth Basin	120	5.0
GCR1 - Well 114	6/23/11	Fort Worth Basin	96	4.0
GCR1 - Well 115	6/23/11	Fort Worth Basin	48	2.0
GCR1 - Well 116	6/24/11	Fort Worth Basin	24	1.0
GCR1 - Well 117	6/25/11	Fort Worth Basin	24	1.0
GCR1 - Well 118	6/28/11	Fort Worth Basin	48	2.0
GCR1 - Well 119	7/11/11	Fort Worth Basin	96	4.0
GCR1 - Well 120	7/19/11	Fort Worth Basin	264	11.0
GCR1 - Well 121	8/1/11	Fort Worth Basin	240	10.0
GCR1 - Well 122	8/1/11	Fort Worth Basin	96	4.0
GCR1 - Well 123	8/1/11	Fort Worth Basin	96	4.0
GCR1 - Well 124	8/1/11	Fort Worth Basin	96	4.0
GCR1 - Well 125	8/1/11	Fort Worth Basin	96	4.0
GCR1 - Well 126	8/2/11	Fort Worth Basin	216	9.0
GCR1 - Well 127	8/9/11	Fort Worth Basin	24	1.0
GCR1 - Well 128	8/15/11	Fort Worth Basin	168	7.0
GCR1 - Well 129	8/17/11	Fort Worth Basin	120	5.0
GCR1 - Well 130	8/19/11	Fort Worth Basin	264	11.0
GCR1 - Well 131	8/19/11	Fort Worth Basin	168	7.0

Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 132	8/23/11	Fort Worth Basin	384	16.0
GCR1 - Well 133	8/23/11	Fort Worth Basin	360	15.0
GCR1 - Well 134	8/23/11	Fort Worth Basin	384	16.0
GCR1 - Well 135	1/12/11	Fort Worth Basin	144	6.0
GCR1 - Well 136	1/12/11	Fort Worth Basin	144	6.0
GCR1 - Well 137	1/13/11	Fort Worth Basin	168	7.0
GCR1 - Well 138	1/14/11	Fort Worth Basin	192	8.0
GCR1 - Well 139	1/17/11	Fort Worth Basin	120	5.0
GCR1 - Well 140	1/18/11	Fort Worth Basin	336	14.0
GCR1 - Well 141	1/18/11	Fort Worth Basin	336	14.0
GCR1 - Well 142	1/18/11	Fort Worth Basin	576	24.0
GCR1 - Well 143	1/20/11	Fort Worth Basin	72	3.0
GCR1 - Well 144	1/21/11	Fort Worth Basin	168	7.0
GCR1 - Well 145	1/25/11	Fort Worth Basin	408	17.0
GCR1 - Well 146	1/26/11	Fort Worth Basin	168	7.0
GCR1 - Well 147	1/26/11	Fort Worth Basin	168	7.0
GCR1 - Well 148	1/27/11	Fort Worth Basin	120	5.0
GCR1 - Well 149	1/27/11	Fort Worth Basin	168	7.0
GCR1 - Well 150	2/6/11	Fort Worth Basin	288	12.0
GCR1 - Well 151	2/8/11	Fort Worth Basin	600	25.0
GCR1 - Well 152	2/8/11	Fort Worth Basin	48	2.0
GCR1 - Well 153	2/9/11	Fort Worth Basin	144	6.0
GCR1 - Well 154	2/9/11	Fort Worth Basin	192	8.0
GCR1 - Well 155	2/12/11	Fort Worth Basin	240	10.0
GCR1 - Well 156	2/12/11	Fort Worth Basin	432	18.0
GCR1 - Well 157	2/14/11	Fort Worth Basin	360	15.0
GCR1 - Well 158	2/15/11	Fort Worth Basin	192	8.0
GCR1 - Well 159	2/16/11	Fort Worth Basin	312	13.0
GCR1 - Well 160	2/17/11	Fort Worth Basin	288	12.0
GCR1 - Well 161	2/19/11	Fort Worth Basin	96	4.0
GCR1 - Well 162	2/23/11	Fort Worth Basin	24	1.0
GCR1 - Well 163	3/12/11	Fort Worth Basin	216	9.0
GCR1 - Well 164	3/21/11	Fort Worth Basin	168	7.0
GCR1 - Well 165	3/22/11	Fort Worth Basin	144	6.0

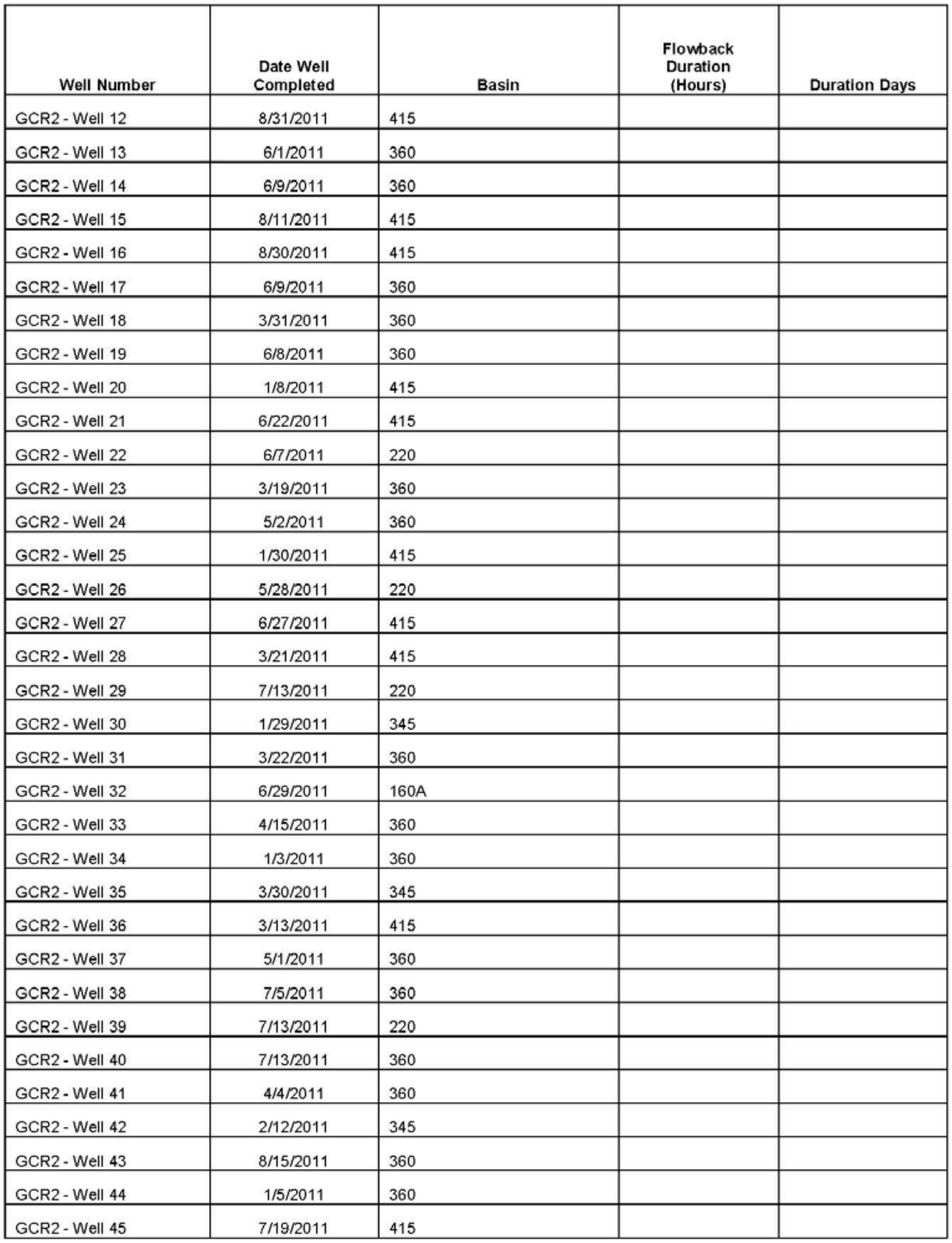
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 166	3/23/11	Fort Worth Basin	168	7.0
GCR1 - Well 167	3/23/11	Fort Worth Basin	168	7.0
GCR1 - Well 168	3/23/11	Fort Worth Basin	168	7.0
GCR1 - Well 169	3/24/11	Fort Worth Basin	144	6.0
GCR1 - Well 170	3/25/11	Fort Worth Basin	192	8.0
GCR1 - Well 171	3/26/11	Fort Worth Basin	96	4.0
GCR1 - Well 172	3/27/11	Fort Worth Basin	72	3.0
GCR1 - Well 173	3/28/11	Fort Worth Basin	120	5.0
GCR1 - Well 174	4/5/11	Fort Worth Basin	240	10.0
GCR1 - Well 175	4/12/11	Fort Worth Basin	72	3.0
GCR1 - Well 176	4/14/11	Fort Worth Basin	360	15.0
GCR1 - Well 177	4/15/11	Fort Worth Basin	312	13.0
GCR1 - Well 178	4/16/11	Fort Worth Basin	312	13.0
GCR1 - Well 179	4/17/11	Fort Worth Basin	72	3.0
GCR1 - Well 180	4/17/11	Fort Worth Basin	360	15.0
GCR1 - Well 181	4/18/11	Fort Worth Basin	24	1.0
GCR1 - Well 182	4/18/11	Fort Worth Basin	144	6.0
GCR1 - Well 183	4/18/11	Fort Worth Basin	264	11.0
GCR1 - Well 184	4/19/11	Fort Worth Basin	96	4.0
GCR1 - Well 185	4/19/11	Fort Worth Basin	120	5.0
GCR1 - Well 186	4/19/11	Fort Worth Basin	168	7.0
GCR1 - Well 187	4/20/11	Fort Worth Basin	96	4.0
GCR1 - Well 188	4/22/11	Fort Worth Basin	120	5.0
GCR1 - Well 189	4/23/11	Fort Worth Basin	192	8.0
GCR1 - Well 190	4/26/11	Fort Worth Basin	120	5.0
GCR1 - Well 191	4/29/11	Fort Worth Basin	48	2.0
GCR1 - Well 192	4/30/11	Fort Worth Basin	24	1.0
GCR1 - Well 193	4/30/11	Fort Worth Basin	384	16.0
GCR1 - Well 194	5/2/11	Fort Worth Basin	48	2.0
GCR1 - Well 195	5/8/11	Fort Worth Basin	144	6.0
GCR1 - Well 196	5/10/11	Fort Worth Basin	312	13.0
GCR1 - Well 197	5/10/11	Fort Worth Basin	312	13.0
GCR1 - Well 198	5/11/11	Fort Worth Basin	168	7.0
GCR1 - Well 199	5/11/11	Fort Worth Basin	288	12.0



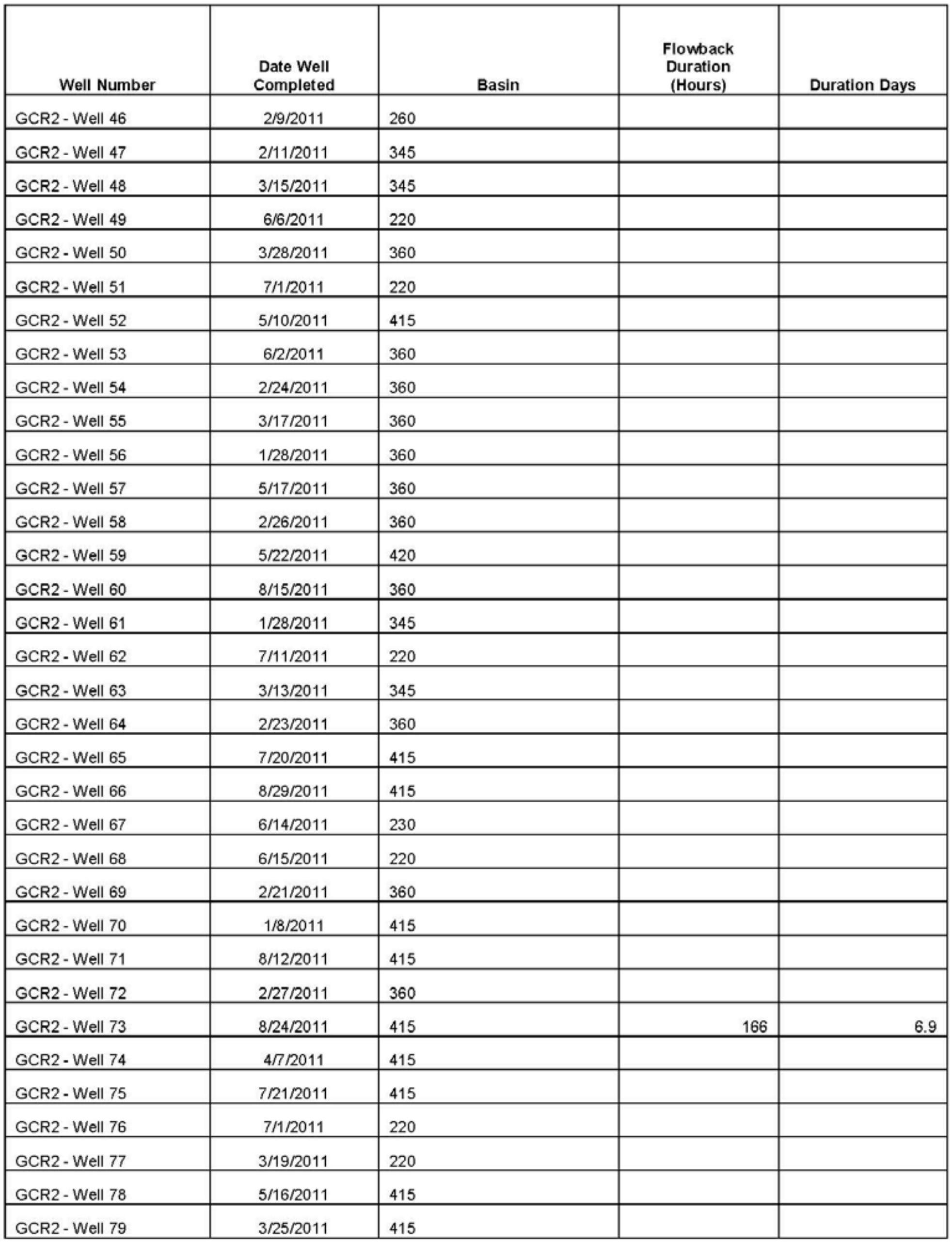
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 200	5/12/11	Fort Worth Basin	144	6.0
GCR1 - Well 201	5/12/11	Fort Worth Basin	168	7.0
GCR1 - Well 202	5/12/11	Fort Worth Basin	264	11.0
GCR1 - Well 203	5/13/11	Fort Worth Basin	120	5.0
GCR1 - Well 204	5/13/11	Fort Worth Basin	144	6.0
GCR1 - Well 205	5/16/11	Fort Worth Basin	168	7.0
GCR1 - Well 206	5/17/11	Fort Worth Basin	144	6.0
GCR1 - Well 207	5/18/11	Fort Worth Basin	168	7.0
GCR1 - Well 208	5/23/11	Fort Worth Basin	96	4.0
GCR1 - Well 209	5/24/11	Fort Worth Basin	72	3.0
GCR1 - Well 210	6/3/11	Fort Worth Basin	192	8.0
GCR1 - Well 211	6/3/11	Fort Worth Basin	192	8.0
GCR1 - Well 212	6/6/11	Fort Worth Basin	192	8.0
GCR1 - Well 213	6/9/11	Fort Worth Basin	168	7.0
GCR1 - Well 214	6/14/11	Fort Worth Basin	144	6.0
GCR1 - Well 215	6/14/11	Fort Worth Basin	144	6.0
GCR1 - Well 216	6/14/11	Fort Worth Basin	144	6.0
GCR1 - Well 217	6/15/11	Fort Worth Basin	120	5.0
GCR1 - Well 218	6/20/11	Fort Worth Basin	192	8.0
GCR1 - Well 219	6/20/11	Fort Worth Basin	192	8.0
GCR1 - Well 220	6/21/11	Fort Worth Basin	168	7.0
GCR1 - Well 221	6/27/11	Fort Worth Basin	120	5.0
GCR1 - Well 222	6/28/11	Fort Worth Basin	144	6.0
GCR1 - Well 223	6/30/11	Fort Worth Basin	264	11.0
GCR1 - Well 224	7/1/11	Fort Worth Basin	264	11.0
GCR1 - Well 225	7/26/11	Fort Worth Basin	192	8.0
GCR1 - Well 226	7/27/11	Fort Worth Basin	384	16.0
GCR1 - Well 227	7/27/11	Fort Worth Basin	216	9.0
GCR1 - Well 228	7/27/11	Fort Worth Basin	288	12.0
GCR1 - Well 229	7/27/11	Fort Worth Basin	168	7.0
GCR1 - Well 230	7/29/11	Fort Worth Basin	144	6.0
GCR1 - Well 231	8/9/11	Fort Worth Basin	72	3.0
GCR1 - Well 232	8/9/11	Fort Worth Basin	168	7.0
GCR1 - Well 233	8/9/11	Fort Worth Basin	216	9.0



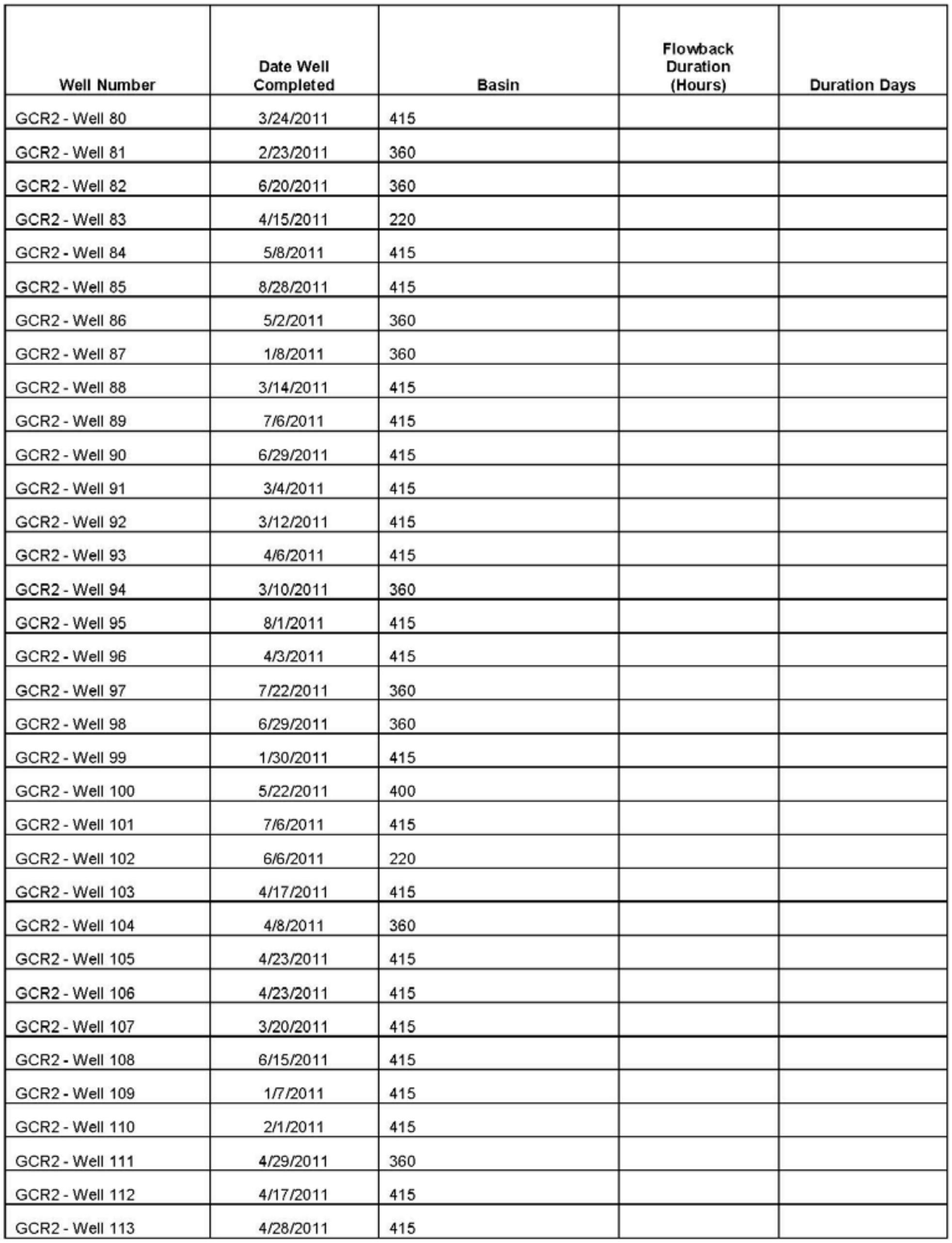
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR1 - Well 234	8/10/11	Fort Worth Basin	312	13.0
GCR1 - Well 235	8/15/11	Fort Worth Basin	48	2.0
GCR1 - Well 236	8/18/11	Fort Worth Basin	96	4.0
GCR1 - Well 237	8/21/11	Fort Worth Basin	216	9.0
GCR1 - Well 238	8/22/11	Fort Worth Basin	48	2.0
GCR1 - Well 239	8/22/11	Fort Worth Basin	144	6.0
GCR1 - Well 240	8/25/11	Fort Worth Basin	96	4.0
GCR1 - Well 241	1/16/11	Groesbeck	192	8.0
GCR1 - Well 242	2/23/11	Groesbeck	54	2.3
GCR1 - Well 243	4/19/11	Groesbeck	364	15.2
GCR1 - Well 244	1/21/11	Groesbeck	72	3.0
GCR1 - Well 245	7/13/11	Groesbeck	325	13.5
GCR1 - Well 246	7/14/11	Groesbeck	463	19.3
GCR1 - Well 247	3/18/11	Groesbeck	355	14.8
GCR1 - Well 248	4/12/11	North LA	294	12.3
GCR1 - Well 249	7/8/11	North LA	474	19.8
GCR1 - Well 250	2/21/11	South Texas	377	15.7
GCR1 - Well 251	7/21/11	South Texas	232	9.7
GCR1 - Well 252	3/11/11	South Texas	3	0.1
GCR1 - Well 253	4/5/11	South Texas	130	5.4
GCR1 - Well 254	8/17/11	South Texas	196	8.2
GCR1 - Well 255	8/9/11	STX - Eagleford	344	14.3
GCR1 - Well 256	8/9/11	STX - Eagleford	330	13.8
GCR2 - Well 1	8/29/2011	360		
GCR2 - Well 2	8/18/2011	415		
GCR2 - Well 3	3/23/2011	160A		
GCR2 - Well 4	3/8/2011	360		
GCR2 - Well 5	4/30/2011	360		
GCR2 - Well 6	2/21/2011	415		
GCR2 - Well 7	7/29/2011	415		
GCR2 - Well 8	2/22/2011	345	136	5.7
GCR2 - Well 9	6/1/2011	360		
GCR2 - Well 10	6/20/2011	360		
GCR2 - Well 11	4/6/2011	360		



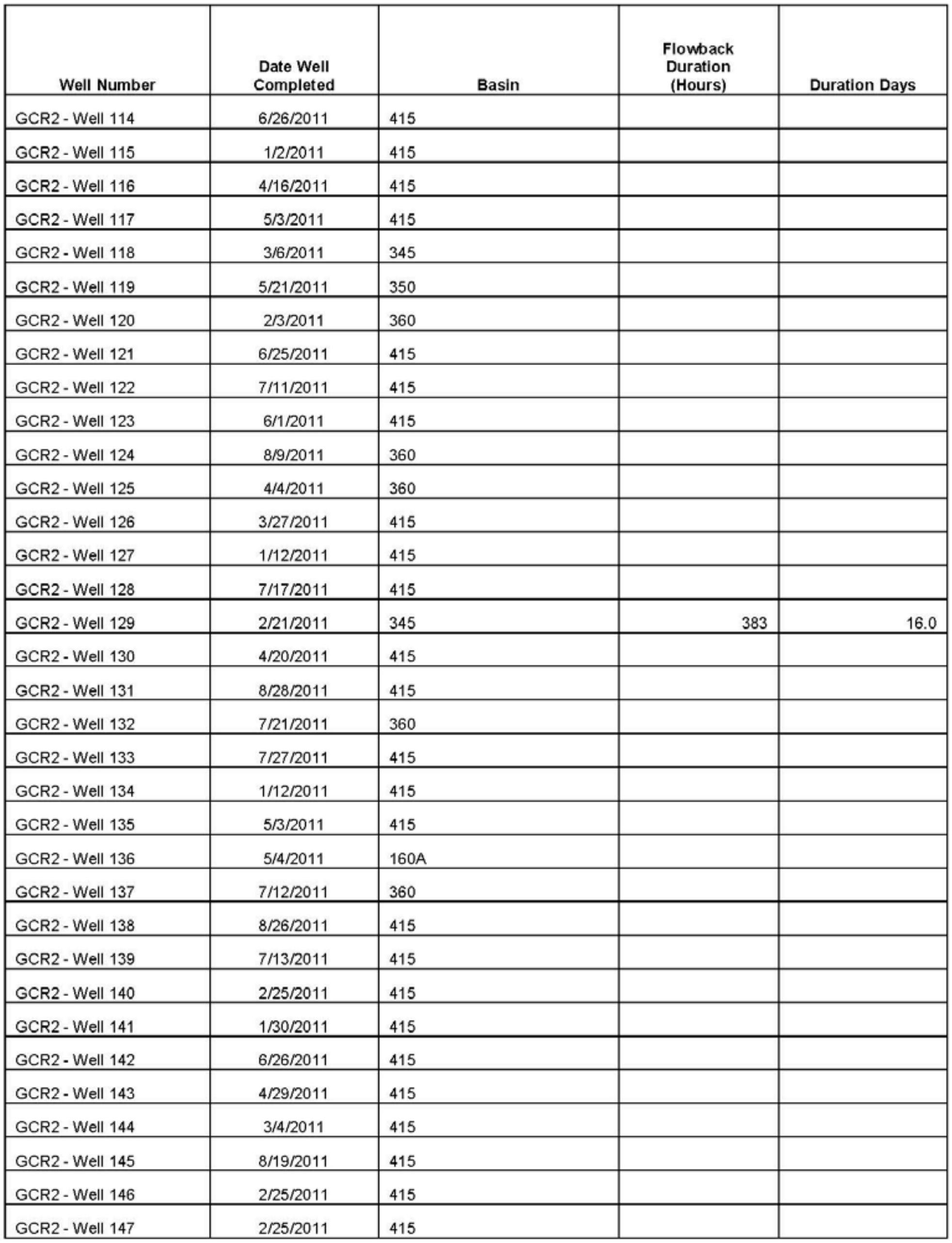
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 12	8/31/2011	415		
GCR2 - Well 13	6/1/2011	360		
GCR2 - Well 14	6/9/2011	360		
GCR2 - Well 15	8/11/2011	415		
GCR2 - Well 16	8/30/2011	415		
GCR2 - Well 17	6/9/2011	360		
GCR2 - Well 18	3/31/2011	360		
GCR2 - Well 19	6/8/2011	360		
GCR2 - Well 20	1/8/2011	415		
GCR2 - Well 21	6/22/2011	415		
GCR2 - Well 22	6/7/2011	220		
GCR2 - Well 23	3/19/2011	360		
GCR2 - Well 24	5/2/2011	360		
GCR2 - Well 25	1/30/2011	415		
GCR2 - Well 26	5/28/2011	220		
GCR2 - Well 27	6/27/2011	415		
GCR2 - Well 28	3/21/2011	415		
GCR2 - Well 29	7/13/2011	220		
GCR2 - Well 30	1/29/2011	345		
GCR2 - Well 31	3/22/2011	360		
GCR2 - Well 32	6/29/2011	160A		
GCR2 - Well 33	4/15/2011	360		
GCR2 - Well 34	1/3/2011	360		
GCR2 - Well 35	3/30/2011	345		
GCR2 - Well 36	3/13/2011	415		
GCR2 - Well 37	5/1/2011	360		
GCR2 - Well 38	7/5/2011	360		
GCR2 - Well 39	7/13/2011	220		
GCR2 - Well 40	7/13/2011	360		
GCR2 - Well 41	4/4/2011	360		
GCR2 - Well 42	2/12/2011	345		
GCR2 - Well 43	8/15/2011	360		
GCR2 - Well 44	1/5/2011	360		
GCR2 - Well 45	7/19/2011	415		



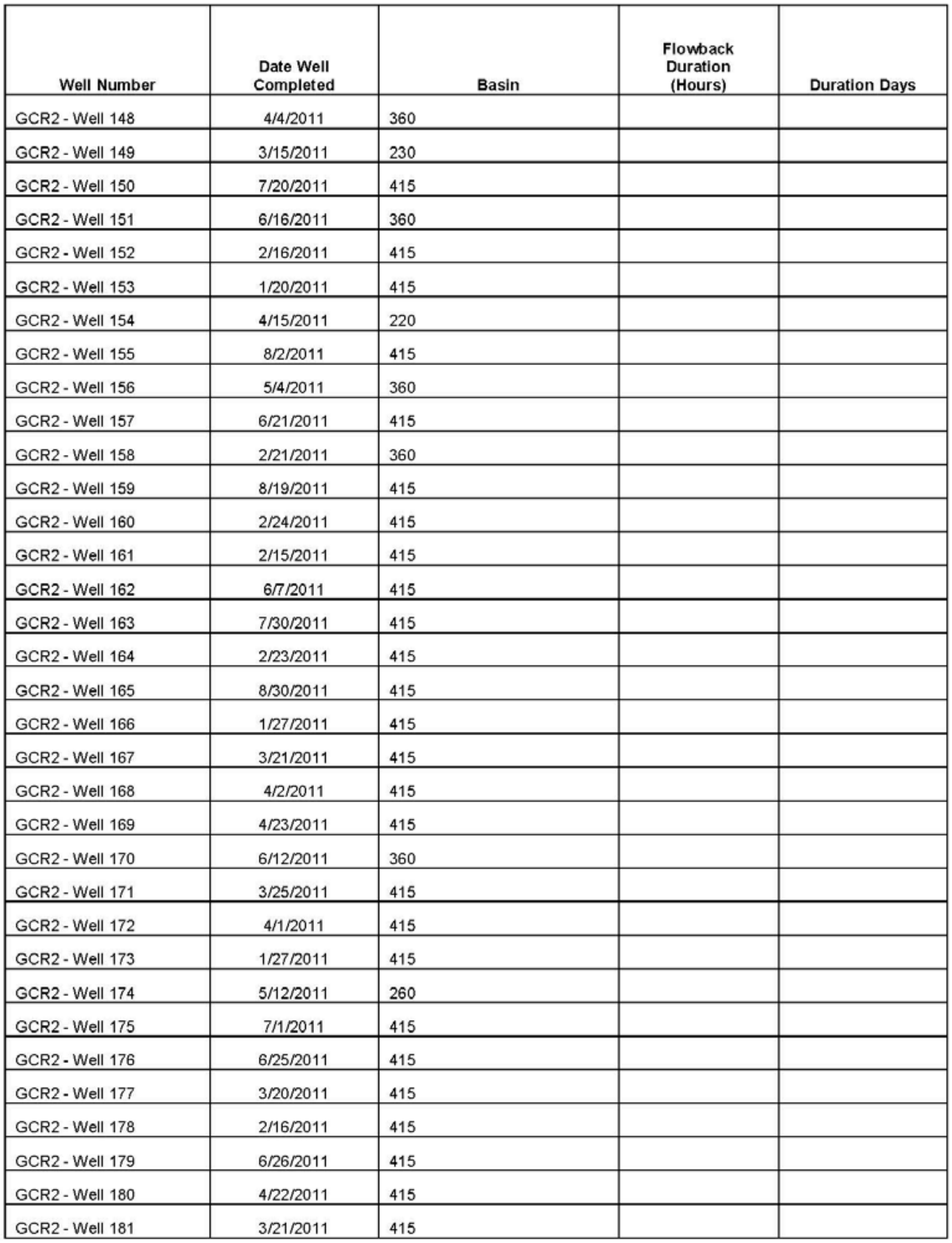
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 46	2/9/2011	260		
GCR2 - Well 47	2/11/2011	345		
GCR2 - Well 48	3/15/2011	345		
GCR2 - Well 49	6/6/2011	220		
GCR2 - Well 50	3/28/2011	360		
GCR2 - Well 51	7/1/2011	220		
GCR2 - Well 52	5/10/2011	415		
GCR2 - Well 53	6/2/2011	360		
GCR2 - Well 54	2/24/2011	360		
GCR2 - Well 55	3/17/2011	360		
GCR2 - Well 56	1/28/2011	360		
GCR2 - Well 57	5/17/2011	360		
GCR2 - Well 58	2/26/2011	360		
GCR2 - Well 59	5/22/2011	420		
GCR2 - Well 60	8/15/2011	360		
GCR2 - Well 61	1/28/2011	345		
GCR2 - Well 62	7/11/2011	220		
GCR2 - Well 63	3/13/2011	345		
GCR2 - Well 64	2/23/2011	360		
GCR2 - Well 65	7/20/2011	415		
GCR2 - Well 66	8/29/2011	415		
GCR2 - Well 67	6/14/2011	230		
GCR2 - Well 68	6/15/2011	220		
GCR2 - Well 69	2/21/2011	360		
GCR2 - Well 70	1/8/2011	415		
GCR2 - Well 71	8/12/2011	415		
GCR2 - Well 72	2/27/2011	360		
GCR2 - Well 73	8/24/2011	415	166	6.9
GCR2 - Well 74	4/7/2011	415		
GCR2 - Well 75	7/21/2011	415		
GCR2 - Well 76	7/1/2011	220		
GCR2 - Well 77	3/19/2011	220		
GCR2 - Well 78	5/16/2011	415		
GCR2 - Well 79	3/25/2011	415		



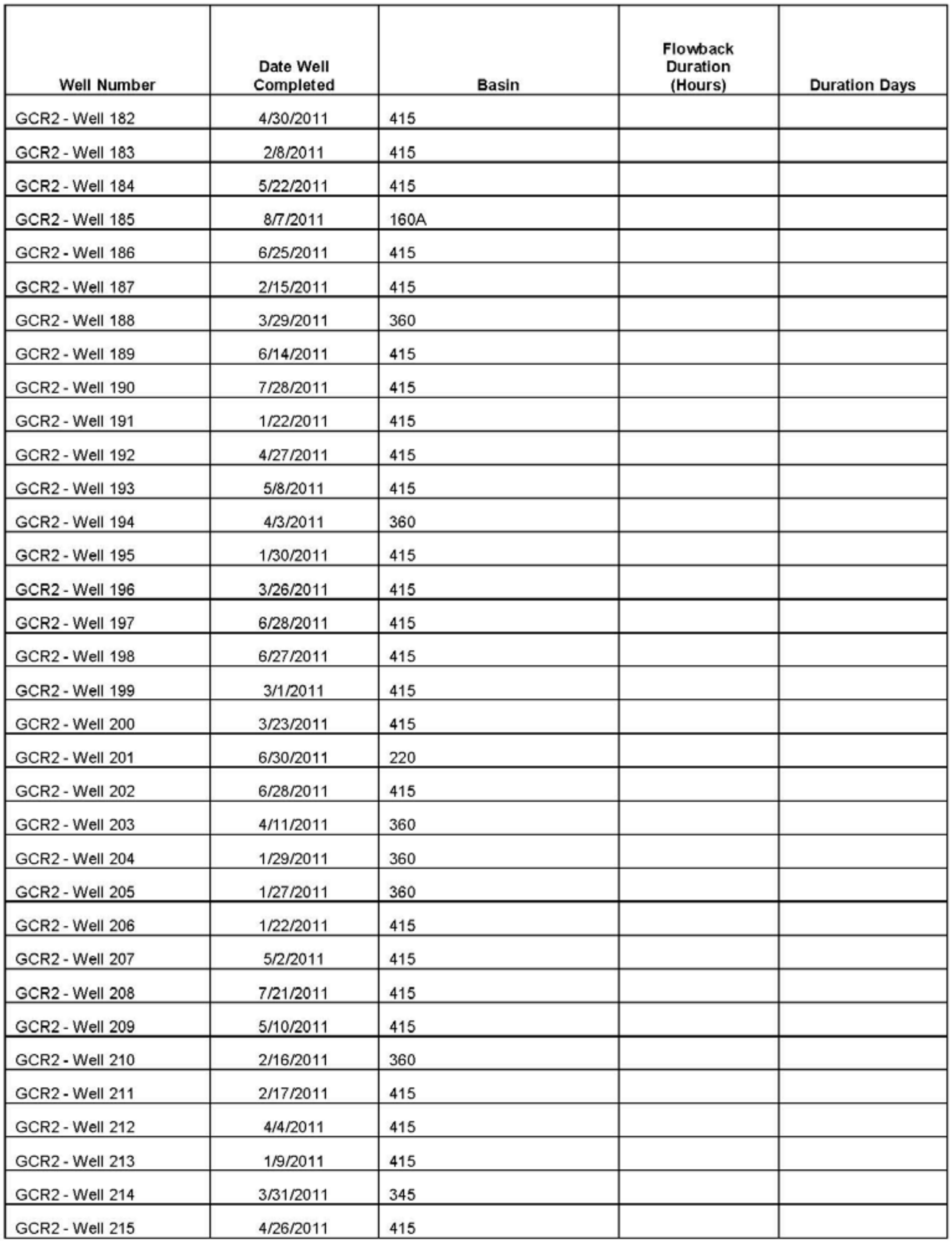
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 80	3/24/2011	415		
GCR2 - Well 81	2/23/2011	360		
GCR2 - Well 82	6/20/2011	360		
GCR2 - Well 83	4/15/2011	220		
GCR2 - Well 84	5/8/2011	415		
GCR2 - Well 85	8/28/2011	415		
GCR2 - Well 86	5/2/2011	360		
GCR2 - Well 87	1/8/2011	360		
GCR2 - Well 88	3/14/2011	415		
GCR2 - Well 89	7/6/2011	415		
GCR2 - Well 90	6/29/2011	415		
GCR2 - Well 91	3/4/2011	415		
GCR2 - Well 92	3/12/2011	415		
GCR2 - Well 93	4/6/2011	415		
GCR2 - Well 94	3/10/2011	360		
GCR2 - Well 95	8/1/2011	415		
GCR2 - Well 96	4/3/2011	415		
GCR2 - Well 97	7/22/2011	360		
GCR2 - Well 98	6/29/2011	360		
GCR2 - Well 99	1/30/2011	415		
GCR2 - Well 100	5/22/2011	400		
GCR2 - Well 101	7/6/2011	415		
GCR2 - Well 102	6/6/2011	220		
GCR2 - Well 103	4/17/2011	415		
GCR2 - Well 104	4/8/2011	360		
GCR2 - Well 105	4/23/2011	415		
GCR2 - Well 106	4/23/2011	415		
GCR2 - Well 107	3/20/2011	415		
GCR2 - Well 108	6/15/2011	415		
GCR2 - Well 109	1/7/2011	415		
GCR2 - Well 110	2/1/2011	415		
GCR2 - Well 111	4/29/2011	360		
GCR2 - Well 112	4/17/2011	415		
GCR2 - Well 113	4/28/2011	415		



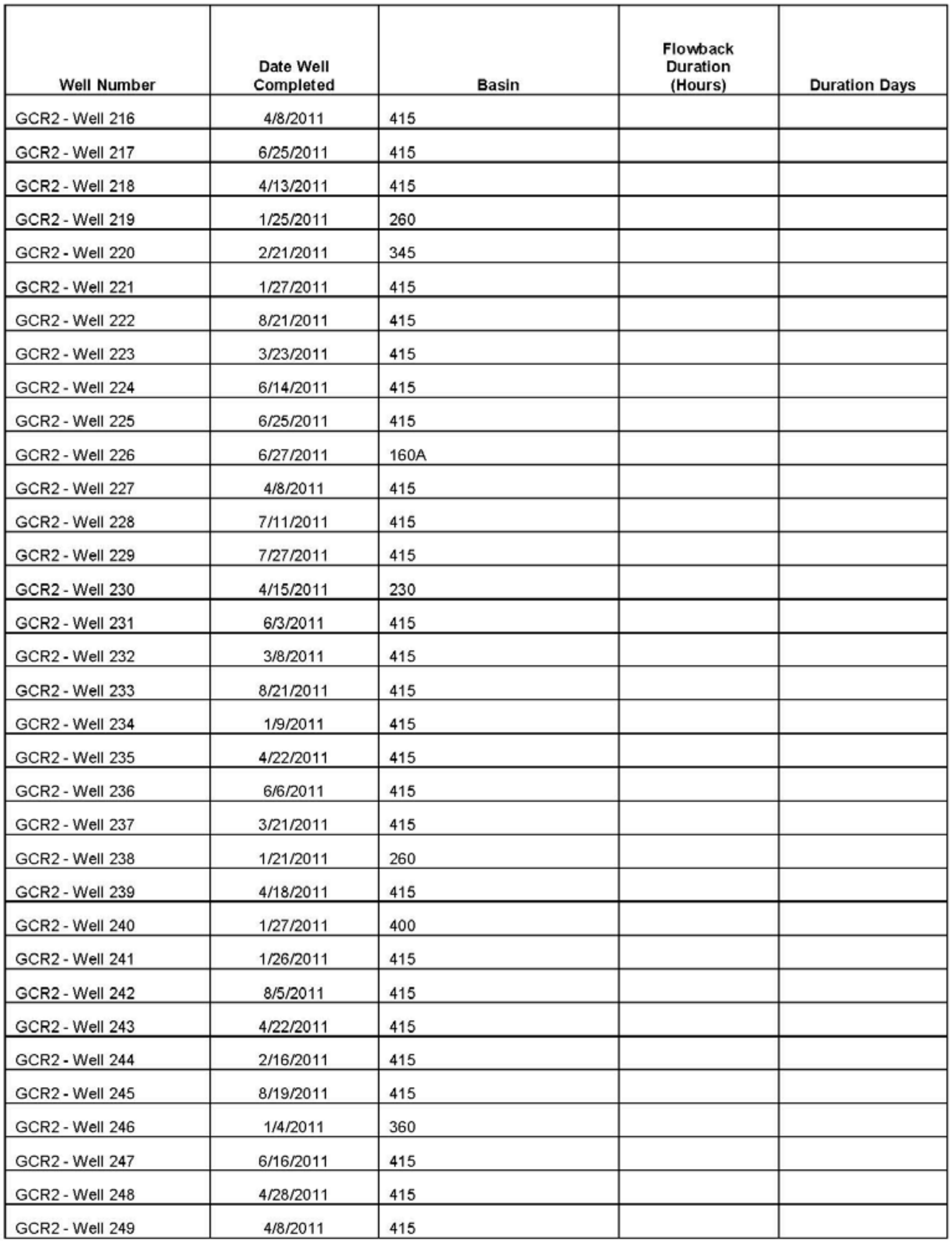
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 114	6/26/2011	415		
GCR2 - Well 115	1/2/2011	415		
GCR2 - Well 116	4/16/2011	415		
GCR2 - Well 117	5/3/2011	415		
GCR2 - Well 118	3/6/2011	345		
GCR2 - Well 119	5/21/2011	350		
GCR2 - Well 120	2/3/2011	360		
GCR2 - Well 121	6/25/2011	415		
GCR2 - Well 122	7/11/2011	415		
GCR2 - Well 123	6/1/2011	415		
GCR2 - Well 124	8/9/2011	360		
GCR2 - Well 125	4/4/2011	360		
GCR2 - Well 126	3/27/2011	415		
GCR2 - Well 127	1/12/2011	415		
GCR2 - Well 128	7/17/2011	415		
GCR2 - Well 129	2/21/2011	345	383	16.0
GCR2 - Well 130	4/20/2011	415		
GCR2 - Well 131	8/28/2011	415		
GCR2 - Well 132	7/21/2011	360		
GCR2 - Well 133	7/27/2011	415		
GCR2 - Well 134	1/12/2011	415		
GCR2 - Well 135	5/3/2011	415		
GCR2 - Well 136	5/4/2011	160A		
GCR2 - Well 137	7/12/2011	360		
GCR2 - Well 138	8/26/2011	415		
GCR2 - Well 139	7/13/2011	415		
GCR2 - Well 140	2/25/2011	415		
GCR2 - Well 141	1/30/2011	415		
GCR2 - Well 142	6/26/2011	415		
GCR2 - Well 143	4/29/2011	415		
GCR2 - Well 144	3/4/2011	415		
GCR2 - Well 145	8/19/2011	415		
GCR2 - Well 146	2/25/2011	415		
GCR2 - Well 147	2/25/2011	415		



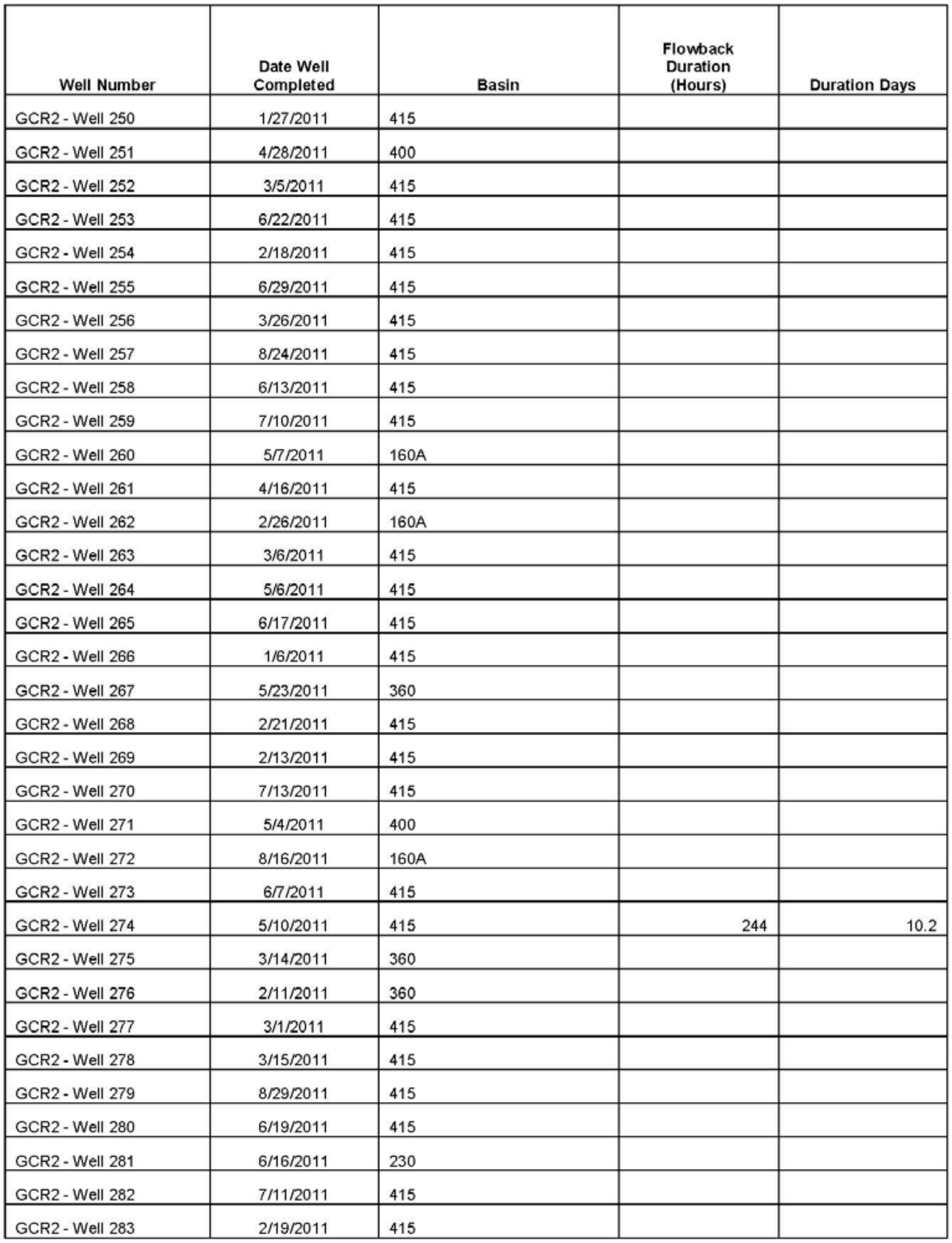
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 148	4/4/2011	360		
GCR2 - Well 149	3/15/2011	230		
GCR2 - Well 150	7/20/2011	415		
GCR2 - Well 151	6/16/2011	360		
GCR2 - Well 152	2/16/2011	415		
GCR2 - Well 153	1/20/2011	415		
GCR2 - Well 154	4/15/2011	220		
GCR2 - Well 155	8/2/2011	415		
GCR2 - Well 156	5/4/2011	360		
GCR2 - Well 157	6/21/2011	415		
GCR2 - Well 158	2/21/2011	360		
GCR2 - Well 159	8/19/2011	415		
GCR2 - Well 160	2/24/2011	415		
GCR2 - Well 161	2/15/2011	415		
GCR2 - Well 162	6/7/2011	415		
GCR2 - Well 163	7/30/2011	415		
GCR2 - Well 164	2/23/2011	415		
GCR2 - Well 165	8/30/2011	415		
GCR2 - Well 166	1/27/2011	415		
GCR2 - Well 167	3/21/2011	415		
GCR2 - Well 168	4/2/2011	415		
GCR2 - Well 169	4/23/2011	415		
GCR2 - Well 170	6/12/2011	360		
GCR2 - Well 171	3/25/2011	415		
GCR2 - Well 172	4/1/2011	415		
GCR2 - Well 173	1/27/2011	415		
GCR2 - Well 174	5/12/2011	260		
GCR2 - Well 175	7/1/2011	415		
GCR2 - Well 176	6/25/2011	415		
GCR2 - Well 177	3/20/2011	415		
GCR2 - Well 178	2/16/2011	415		
GCR2 - Well 179	6/26/2011	415		
GCR2 - Well 180	4/22/2011	415		
GCR2 - Well 181	3/21/2011	415		



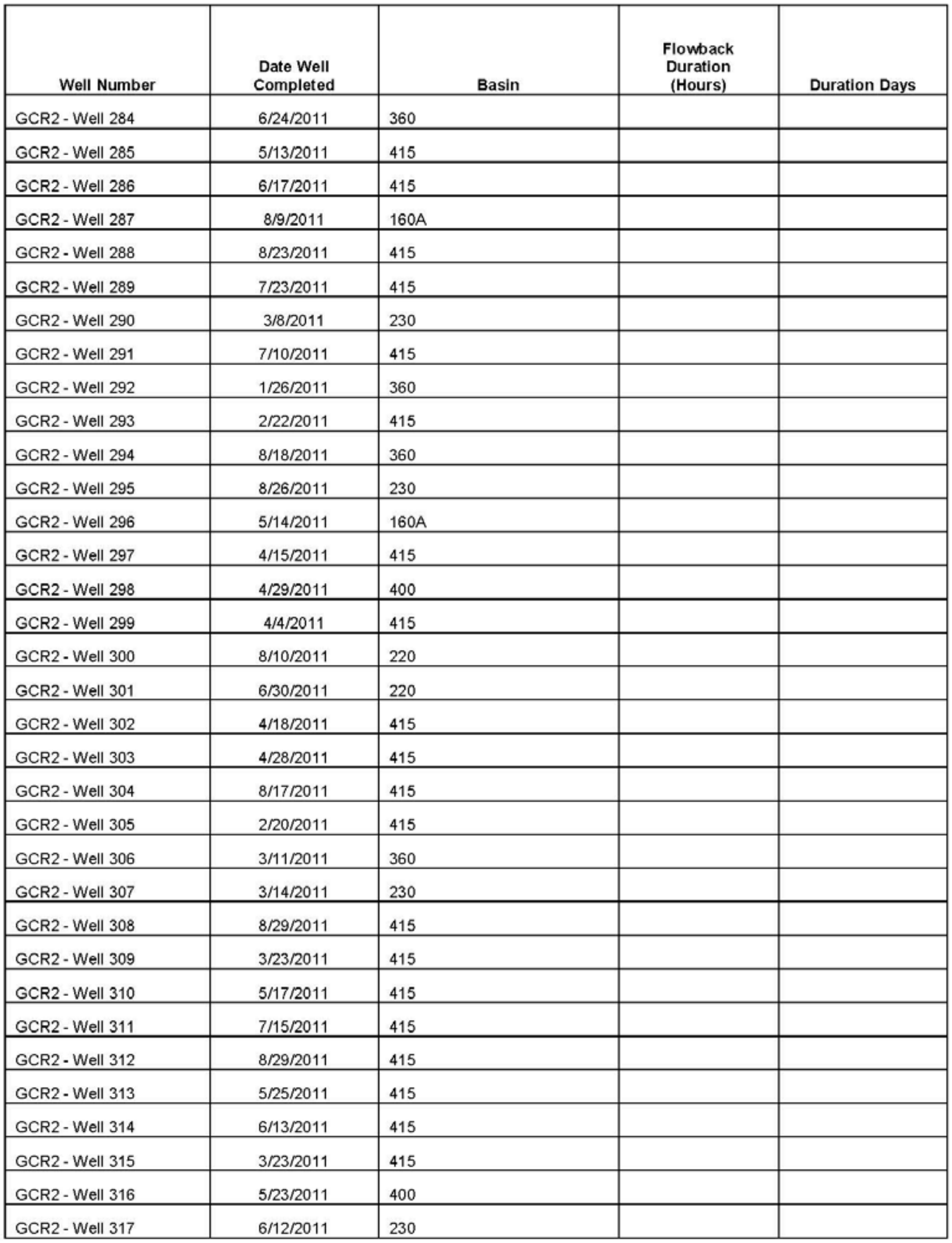
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 182	4/30/2011	415		
GCR2 - Well 183	2/8/2011	415		
GCR2 - Well 184	5/22/2011	415		
GCR2 - Well 185	8/7/2011	160A		
GCR2 - Well 186	6/25/2011	415		
GCR2 - Well 187	2/15/2011	415		
GCR2 - Well 188	3/29/2011	360		
GCR2 - Well 189	6/14/2011	415		
GCR2 - Well 190	7/28/2011	415		
GCR2 - Well 191	1/22/2011	415		
GCR2 - Well 192	4/27/2011	415		
GCR2 - Well 193	5/8/2011	415		
GCR2 - Well 194	4/3/2011	360		
GCR2 - Well 195	1/30/2011	415		
GCR2 - Well 196	3/26/2011	415		
GCR2 - Well 197	6/28/2011	415		
GCR2 - Well 198	6/27/2011	415		
GCR2 - Well 199	3/1/2011	415		
GCR2 - Well 200	3/23/2011	415		
GCR2 - Well 201	6/30/2011	220		
GCR2 - Well 202	6/28/2011	415		
GCR2 - Well 203	4/11/2011	360		
GCR2 - Well 204	1/29/2011	360		
GCR2 - Well 205	1/27/2011	360		
GCR2 - Well 206	1/22/2011	415		
GCR2 - Well 207	5/2/2011	415		
GCR2 - Well 208	7/21/2011	415		
GCR2 - Well 209	5/10/2011	415		
GCR2 - Well 210	2/16/2011	360		
GCR2 - Well 211	2/17/2011	415		
GCR2 - Well 212	4/4/2011	415		
GCR2 - Well 213	1/9/2011	415		
GCR2 - Well 214	3/31/2011	345		
GCR2 - Well 215	4/26/2011	415		



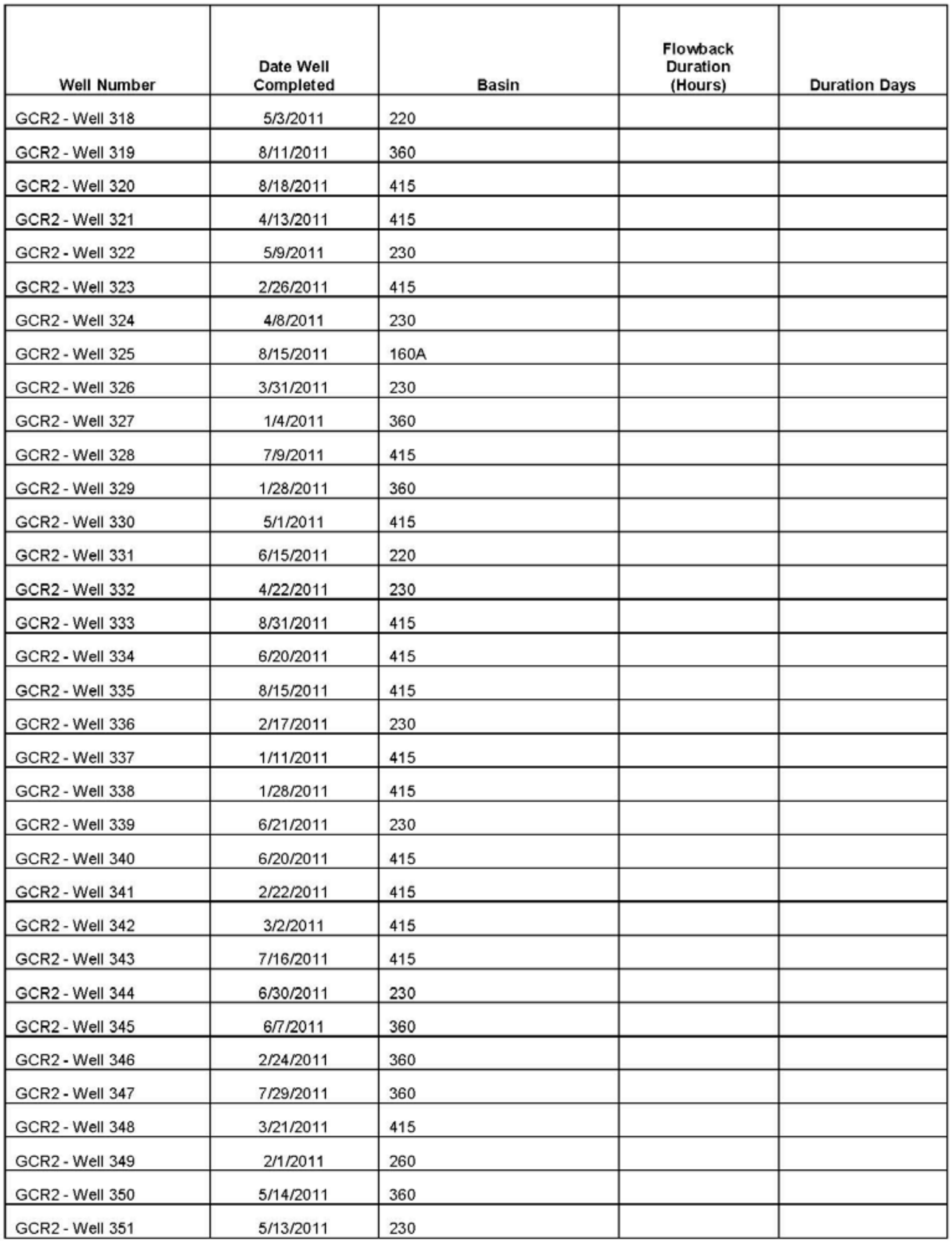
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 216	4/8/2011	415		
GCR2 - Well 217	6/25/2011	415		
GCR2 - Well 218	4/13/2011	415		
GCR2 - Well 219	1/25/2011	260		
GCR2 - Well 220	2/21/2011	345		
GCR2 - Well 221	1/27/2011	415		
GCR2 - Well 222	8/21/2011	415		
GCR2 - Well 223	3/23/2011	415		
GCR2 - Well 224	6/14/2011	415		
GCR2 - Well 225	6/25/2011	415		
GCR2 - Well 226	6/27/2011	160A		
GCR2 - Well 227	4/8/2011	415		
GCR2 - Well 228	7/11/2011	415		
GCR2 - Well 229	7/27/2011	415		
GCR2 - Well 230	4/15/2011	230		
GCR2 - Well 231	6/3/2011	415		
GCR2 - Well 232	3/8/2011	415		
GCR2 - Well 233	8/21/2011	415		
GCR2 - Well 234	1/9/2011	415		
GCR2 - Well 235	4/22/2011	415		
GCR2 - Well 236	6/6/2011	415		
GCR2 - Well 237	3/21/2011	415		
GCR2 - Well 238	1/21/2011	260		
GCR2 - Well 239	4/18/2011	415		
GCR2 - Well 240	1/27/2011	400		
GCR2 - Well 241	1/26/2011	415		
GCR2 - Well 242	8/5/2011	415		
GCR2 - Well 243	4/22/2011	415		
GCR2 - Well 244	2/16/2011	415		
GCR2 - Well 245	8/19/2011	415		
GCR2 - Well 246	1/4/2011	360		
GCR2 - Well 247	6/16/2011	415		
GCR2 - Well 248	4/28/2011	415		
GCR2 - Well 249	4/8/2011	415		



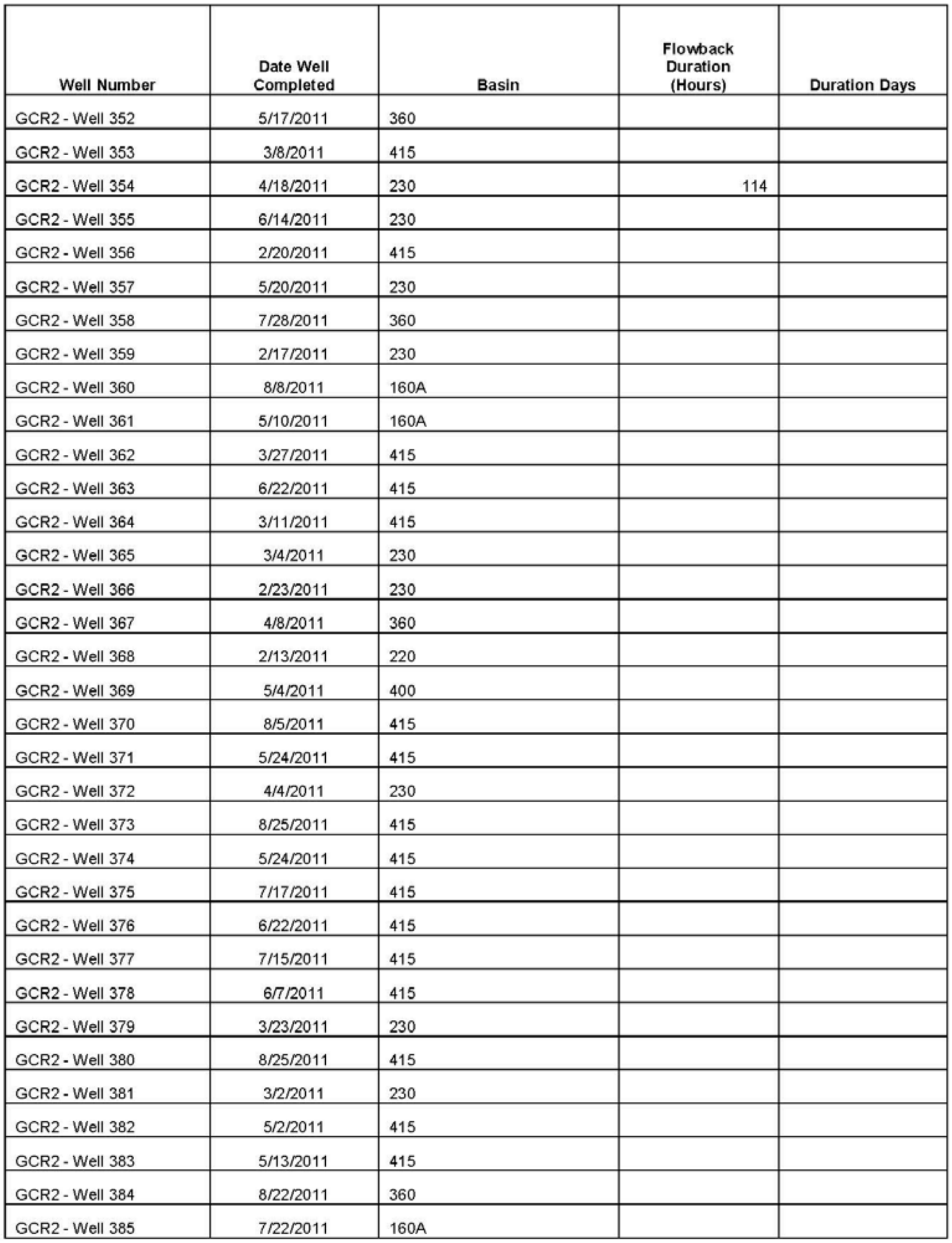
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 250	1/27/2011	415		
GCR2 - Well 251	4/28/2011	400		
GCR2 - Well 252	3/5/2011	415		
GCR2 - Well 253	6/22/2011	415		
GCR2 - Well 254	2/18/2011	415		
GCR2 - Well 255	6/29/2011	415		
GCR2 - Well 256	3/26/2011	415		
GCR2 - Well 257	8/24/2011	415		
GCR2 - Well 258	6/13/2011	415		
GCR2 - Well 259	7/10/2011	415		
GCR2 - Well 260	5/7/2011	160A		
GCR2 - Well 261	4/16/2011	415		
GCR2 - Well 262	2/26/2011	160A		
GCR2 - Well 263	3/6/2011	415		
GCR2 - Well 264	5/6/2011	415		
GCR2 - Well 265	6/17/2011	415		
GCR2 - Well 266	1/6/2011	415		
GCR2 - Well 267	5/23/2011	360		
GCR2 - Well 268	2/21/2011	415		
GCR2 - Well 269	2/13/2011	415		
GCR2 - Well 270	7/13/2011	415		
GCR2 - Well 271	5/4/2011	400		
GCR2 - Well 272	8/16/2011	160A		
GCR2 - Well 273	6/7/2011	415		
GCR2 - Well 274	5/10/2011	415	244	10.2
GCR2 - Well 275	3/14/2011	360		
GCR2 - Well 276	2/11/2011	360		
GCR2 - Well 277	3/1/2011	415		
GCR2 - Well 278	3/15/2011	415		
GCR2 - Well 279	8/29/2011	415		
GCR2 - Well 280	6/19/2011	415		
GCR2 - Well 281	6/16/2011	230		
GCR2 - Well 282	7/11/2011	415		
GCR2 - Well 283	2/19/2011	415		



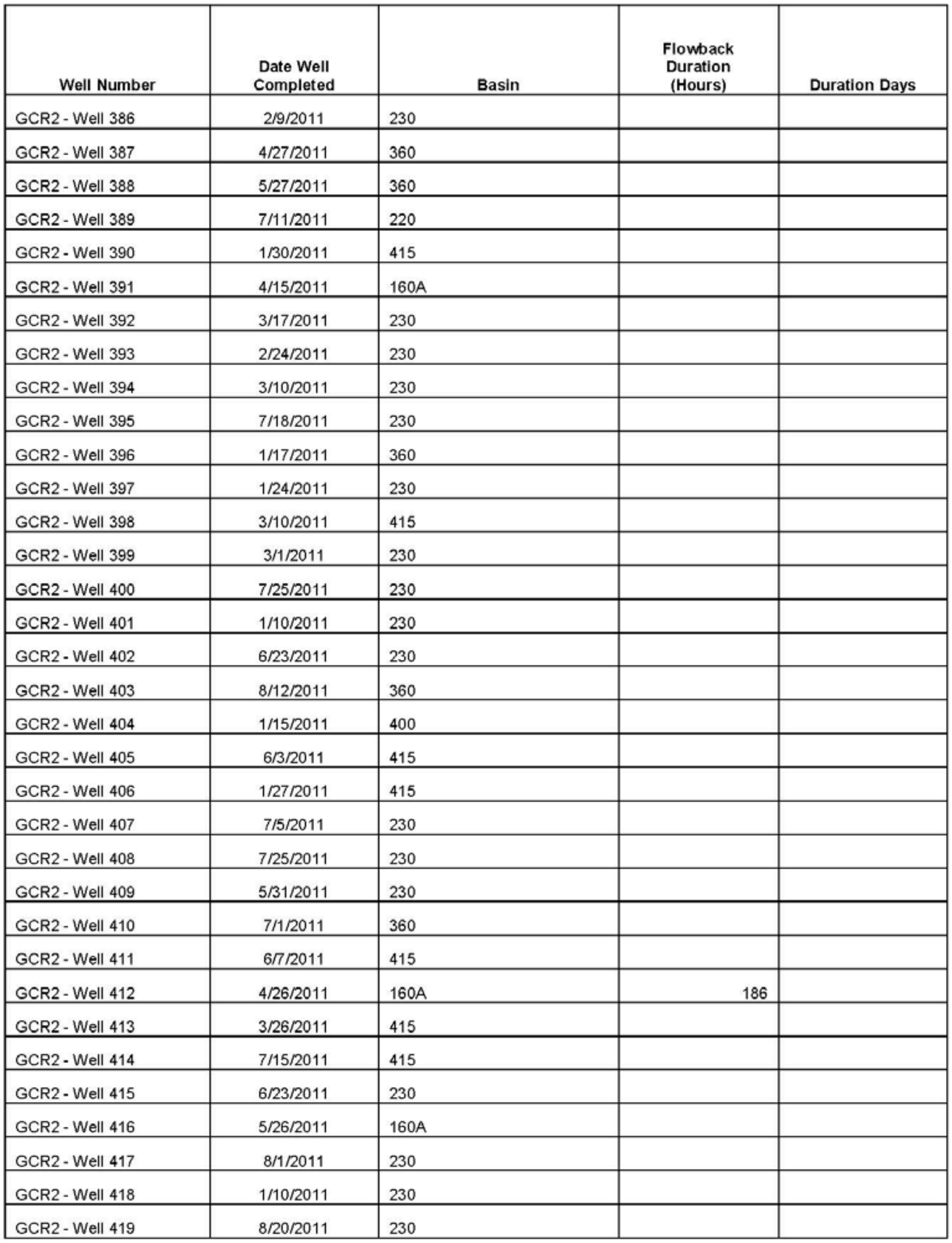
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 284	6/24/2011	360		
GCR2 - Well 285	5/13/2011	415		
GCR2 - Well 286	6/17/2011	415		
GCR2 - Well 287	8/9/2011	160A		
GCR2 - Well 288	8/23/2011	415		
GCR2 - Well 289	7/23/2011	415		
GCR2 - Well 290	3/8/2011	230		
GCR2 - Well 291	7/10/2011	415		
GCR2 - Well 292	1/26/2011	360		
GCR2 - Well 293	2/22/2011	415		
GCR2 - Well 294	8/18/2011	360		
GCR2 - Well 295	8/26/2011	230		
GCR2 - Well 296	5/14/2011	160A		
GCR2 - Well 297	4/15/2011	415		
GCR2 - Well 298	4/29/2011	400		
GCR2 - Well 299	4/4/2011	415		
GCR2 - Well 300	8/10/2011	220		
GCR2 - Well 301	6/30/2011	220		
GCR2 - Well 302	4/18/2011	415		
GCR2 - Well 303	4/28/2011	415		
GCR2 - Well 304	8/17/2011	415		
GCR2 - Well 305	2/20/2011	415		
GCR2 - Well 306	3/11/2011	360		
GCR2 - Well 307	3/14/2011	230		
GCR2 - Well 308	8/29/2011	415		
GCR2 - Well 309	3/23/2011	415		
GCR2 - Well 310	5/17/2011	415		
GCR2 - Well 311	7/15/2011	415		
GCR2 - Well 312	8/29/2011	415		
GCR2 - Well 313	5/25/2011	415		
GCR2 - Well 314	6/13/2011	415		
GCR2 - Well 315	3/23/2011	415		
GCR2 - Well 316	5/23/2011	400		
GCR2 - Well 317	6/12/2011	230		



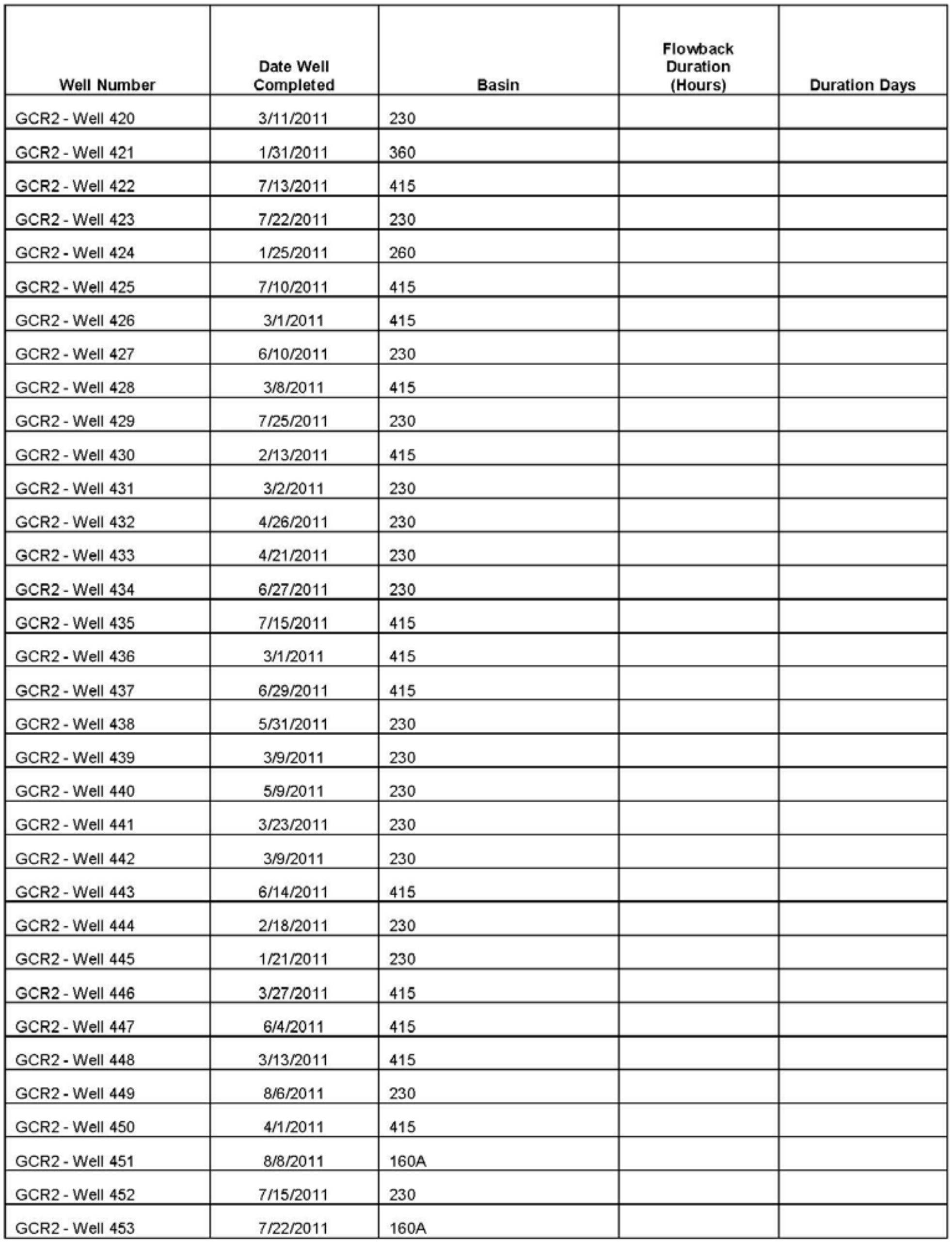
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 318	5/3/2011	220		
GCR2 - Well 319	8/11/2011	360		
GCR2 - Well 320	8/18/2011	415		
GCR2 - Well 321	4/13/2011	415		
GCR2 - Well 322	5/9/2011	230		
GCR2 - Well 323	2/26/2011	415		
GCR2 - Well 324	4/8/2011	230		
GCR2 - Well 325	8/15/2011	160A		
GCR2 - Well 326	3/31/2011	230		
GCR2 - Well 327	1/4/2011	360		
GCR2 - Well 328	7/9/2011	415		
GCR2 - Well 329	1/28/2011	360		
GCR2 - Well 330	5/1/2011	415		
GCR2 - Well 331	6/15/2011	220		
GCR2 - Well 332	4/22/2011	230		
GCR2 - Well 333	8/31/2011	415		
GCR2 - Well 334	6/20/2011	415		
GCR2 - Well 335	8/15/2011	415		
GCR2 - Well 336	2/17/2011	230		
GCR2 - Well 337	1/11/2011	415		
GCR2 - Well 338	1/28/2011	415		
GCR2 - Well 339	6/21/2011	230		
GCR2 - Well 340	6/20/2011	415		
GCR2 - Well 341	2/22/2011	415		
GCR2 - Well 342	3/2/2011	415		
GCR2 - Well 343	7/16/2011	415		
GCR2 - Well 344	6/30/2011	230		
GCR2 - Well 345	6/7/2011	360		
GCR2 - Well 346	2/24/2011	360		
GCR2 - Well 347	7/29/2011	360		
GCR2 - Well 348	3/21/2011	415		
GCR2 - Well 349	2/1/2011	260		
GCR2 - Well 350	5/14/2011	360		
GCR2 - Well 351	5/13/2011	230		



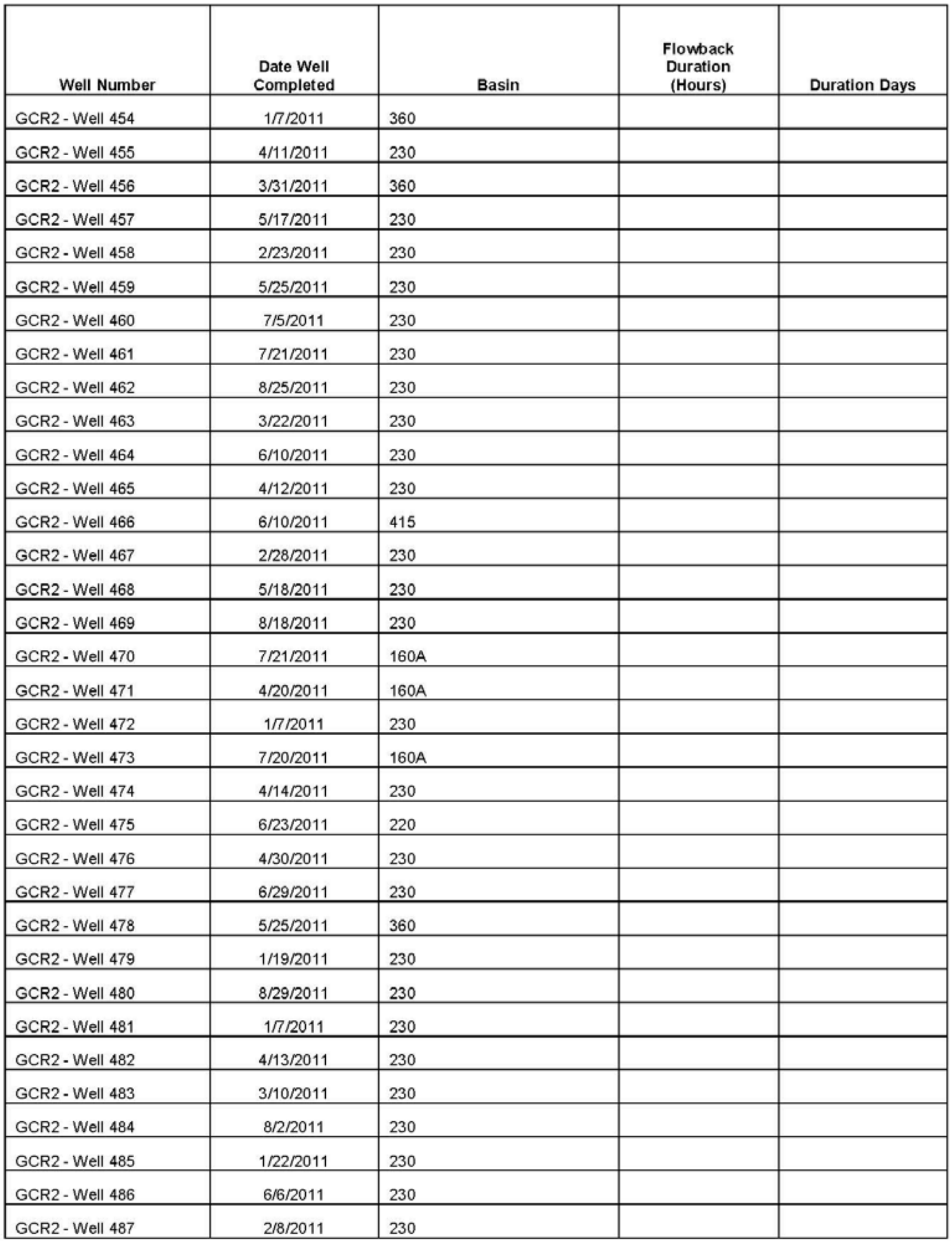
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 352	5/17/2011	360		
GCR2 - Well 353	3/8/2011	415		
GCR2 - Well 354	4/18/2011	230	114	
GCR2 - Well 355	6/14/2011	230		
GCR2 - Well 356	2/20/2011	415		
GCR2 - Well 357	5/20/2011	230		
GCR2 - Well 358	7/28/2011	360		
GCR2 - Well 359	2/17/2011	230		
GCR2 - Well 360	8/8/2011	160A		
GCR2 - Well 361	5/10/2011	160A		
GCR2 - Well 362	3/27/2011	415		
GCR2 - Well 363	6/22/2011	415		
GCR2 - Well 364	3/11/2011	415		
GCR2 - Well 365	3/4/2011	230		
GCR2 - Well 366	2/23/2011	230		
GCR2 - Well 367	4/8/2011	360		
GCR2 - Well 368	2/13/2011	220		
GCR2 - Well 369	5/4/2011	400		
GCR2 - Well 370	8/5/2011	415		
GCR2 - Well 371	5/24/2011	415		
GCR2 - Well 372	4/4/2011	230		
GCR2 - Well 373	8/25/2011	415		
GCR2 - Well 374	5/24/2011	415		
GCR2 - Well 375	7/17/2011	415		
GCR2 - Well 376	6/22/2011	415		
GCR2 - Well 377	7/15/2011	415		
GCR2 - Well 378	6/7/2011	415		
GCR2 - Well 379	3/23/2011	230		
GCR2 - Well 380	8/25/2011	415		
GCR2 - Well 381	3/2/2011	230		
GCR2 - Well 382	5/2/2011	415		
GCR2 - Well 383	5/13/2011	415		
GCR2 - Well 384	8/22/2011	360		
GCR2 - Well 385	7/22/2011	160A		



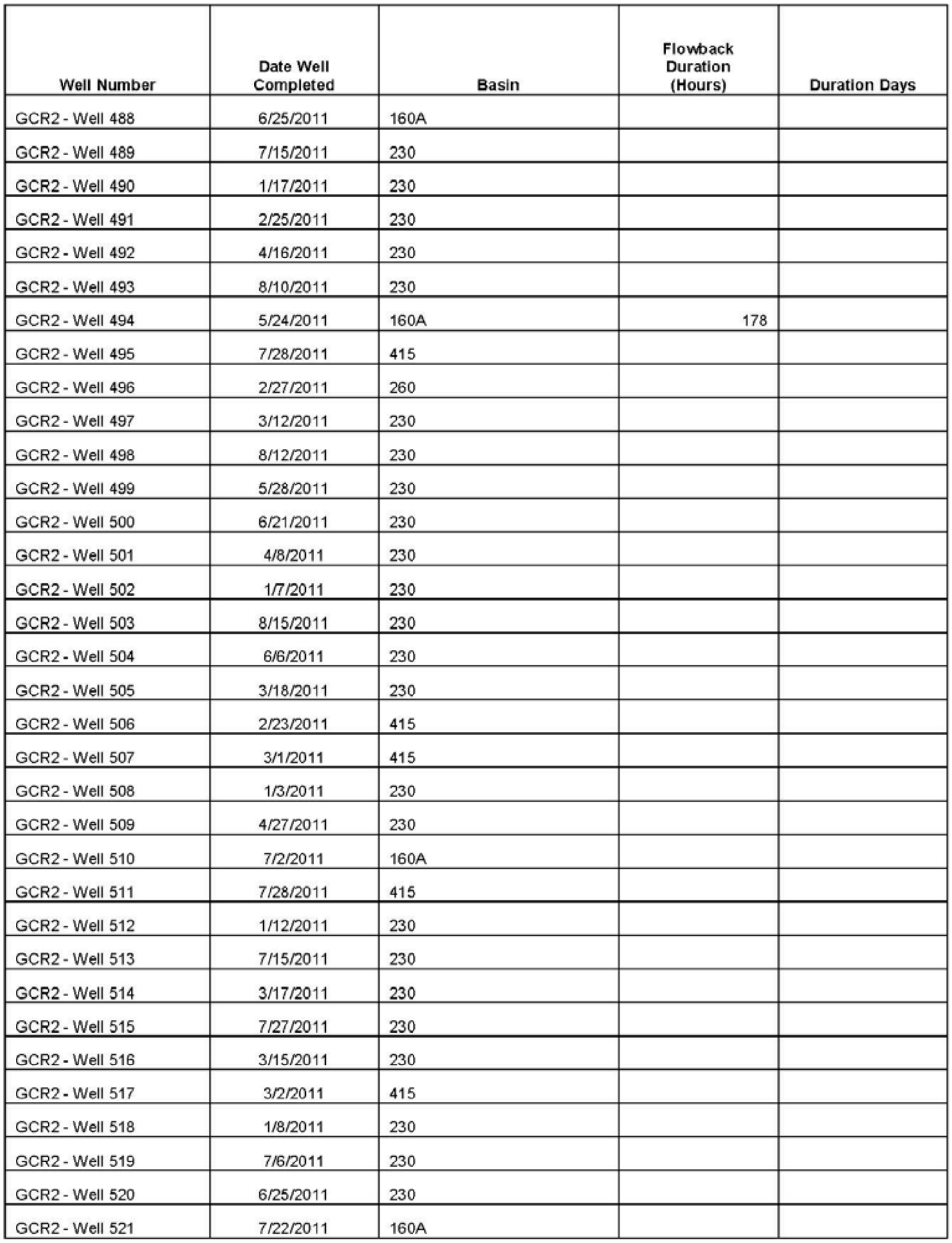
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 386	2/9/2011	230		
GCR2 - Well 387	4/27/2011	360		
GCR2 - Well 388	5/27/2011	360		
GCR2 - Well 389	7/11/2011	220		
GCR2 - Well 390	1/30/2011	415		
GCR2 - Well 391	4/15/2011	160A		
GCR2 - Well 392	3/17/2011	230		
GCR2 - Well 393	2/24/2011	230		
GCR2 - Well 394	3/10/2011	230		
GCR2 - Well 395	7/18/2011	230		
GCR2 - Well 396	1/17/2011	360		
GCR2 - Well 397	1/24/2011	230		
GCR2 - Well 398	3/10/2011	415		
GCR2 - Well 399	3/1/2011	230		
GCR2 - Well 400	7/25/2011	230		
GCR2 - Well 401	1/10/2011	230		
GCR2 - Well 402	6/23/2011	230		
GCR2 - Well 403	8/12/2011	360		
GCR2 - Well 404	1/15/2011	400		
GCR2 - Well 405	6/3/2011	415		
GCR2 - Well 406	1/27/2011	415		
GCR2 - Well 407	7/5/2011	230		
GCR2 - Well 408	7/25/2011	230		
GCR2 - Well 409	5/31/2011	230		
GCR2 - Well 410	7/1/2011	360		
GCR2 - Well 411	6/7/2011	415		
GCR2 - Well 412	4/26/2011	160A	186	
GCR2 - Well 413	3/26/2011	415		
GCR2 - Well 414	7/15/2011	415		
GCR2 - Well 415	6/23/2011	230		
GCR2 - Well 416	5/26/2011	160A		
GCR2 - Well 417	8/1/2011	230		
GCR2 - Well 418	1/10/2011	230		
GCR2 - Well 419	8/20/2011	230		



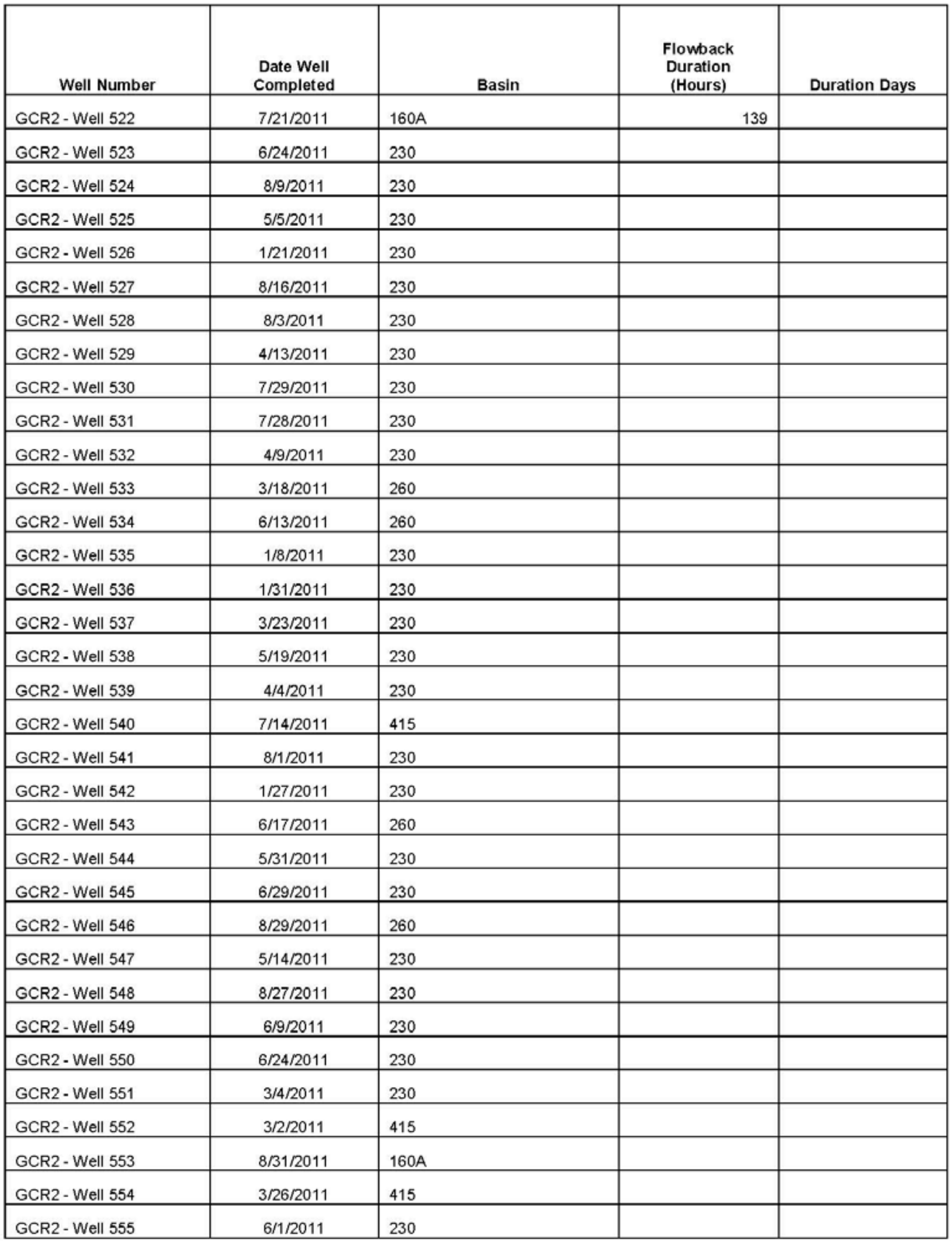
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 420	3/11/2011	230		
GCR2 - Well 421	1/31/2011	360		
GCR2 - Well 422	7/13/2011	415		
GCR2 - Well 423	7/22/2011	230		
GCR2 - Well 424	1/25/2011	260		
GCR2 - Well 425	7/10/2011	415		
GCR2 - Well 426	3/1/2011	415		
GCR2 - Well 427	6/10/2011	230		
GCR2 - Well 428	3/8/2011	415		
GCR2 - Well 429	7/25/2011	230		
GCR2 - Well 430	2/13/2011	415		
GCR2 - Well 431	3/2/2011	230		
GCR2 - Well 432	4/26/2011	230		
GCR2 - Well 433	4/21/2011	230		
GCR2 - Well 434	6/27/2011	230		
GCR2 - Well 435	7/15/2011	415		
GCR2 - Well 436	3/1/2011	415		
GCR2 - Well 437	6/29/2011	415		
GCR2 - Well 438	5/31/2011	230		
GCR2 - Well 439	3/9/2011	230		
GCR2 - Well 440	5/9/2011	230		
GCR2 - Well 441	3/23/2011	230		
GCR2 - Well 442	3/9/2011	230		
GCR2 - Well 443	6/14/2011	415		
GCR2 - Well 444	2/18/2011	230		
GCR2 - Well 445	1/21/2011	230		
GCR2 - Well 446	3/27/2011	415		
GCR2 - Well 447	6/4/2011	415		
GCR2 - Well 448	3/13/2011	415		
GCR2 - Well 449	8/6/2011	230		
GCR2 - Well 450	4/1/2011	415		
GCR2 - Well 451	8/8/2011	160A		
GCR2 - Well 452	7/15/2011	230		
GCR2 - Well 453	7/22/2011	160A		



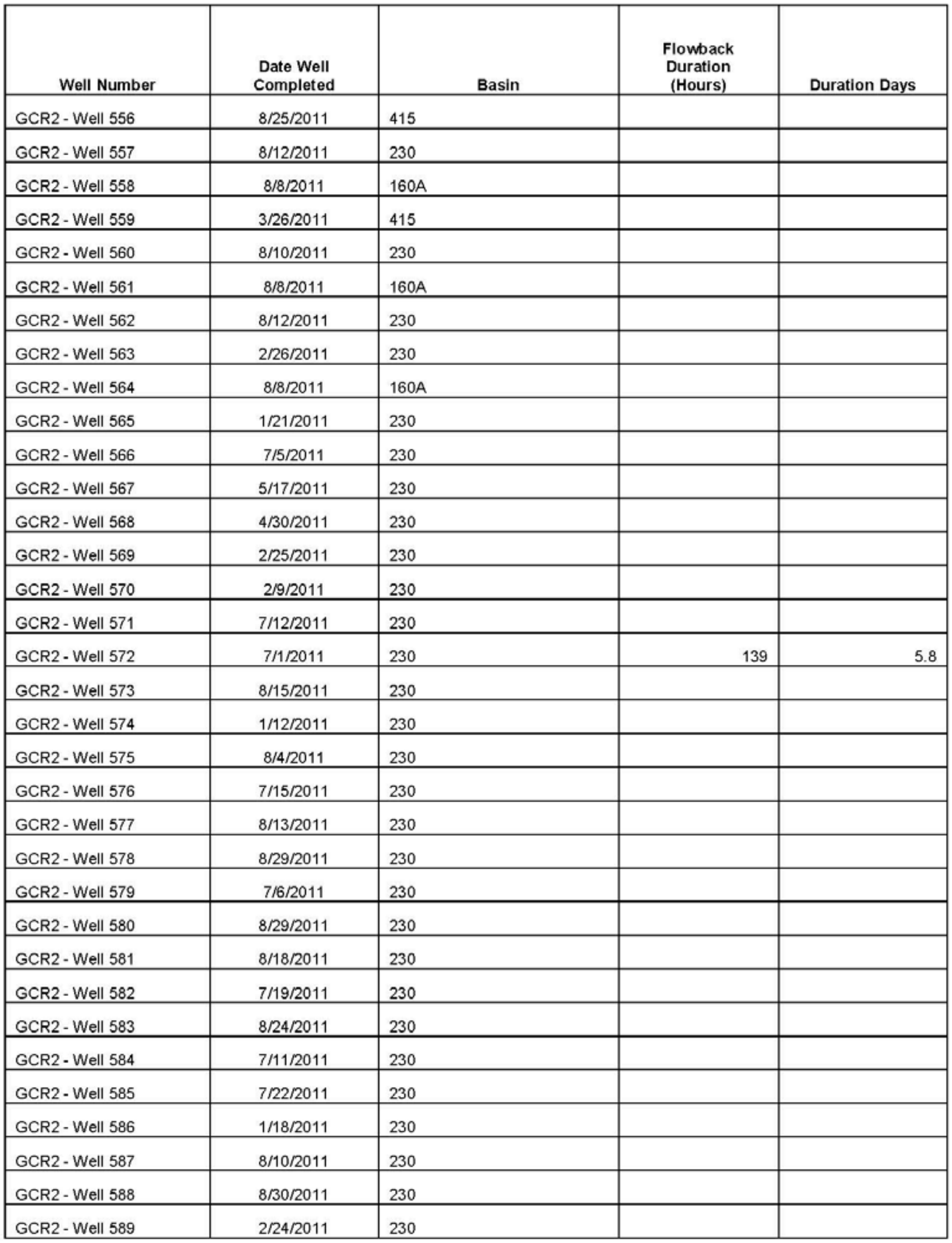
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 454	1/7/2011	360		
GCR2 - Well 455	4/11/2011	230		
GCR2 - Well 456	3/31/2011	360		
GCR2 - Well 457	5/17/2011	230		
GCR2 - Well 458	2/23/2011	230		
GCR2 - Well 459	5/25/2011	230		
GCR2 - Well 460	7/5/2011	230		
GCR2 - Well 461	7/21/2011	230		
GCR2 - Well 462	8/25/2011	230		
GCR2 - Well 463	3/22/2011	230		
GCR2 - Well 464	6/10/2011	230		
GCR2 - Well 465	4/12/2011	230		
GCR2 - Well 466	6/10/2011	415		
GCR2 - Well 467	2/28/2011	230		
GCR2 - Well 468	5/18/2011	230		
GCR2 - Well 469	8/18/2011	230		
GCR2 - Well 470	7/21/2011	160A		
GCR2 - Well 471	4/20/2011	160A		
GCR2 - Well 472	1/7/2011	230		
GCR2 - Well 473	7/20/2011	160A		
GCR2 - Well 474	4/14/2011	230		
GCR2 - Well 475	6/23/2011	220		
GCR2 - Well 476	4/30/2011	230		
GCR2 - Well 477	6/29/2011	230		
GCR2 - Well 478	5/25/2011	360		
GCR2 - Well 479	1/19/2011	230		
GCR2 - Well 480	8/29/2011	230		
GCR2 - Well 481	1/7/2011	230		
GCR2 - Well 482	4/13/2011	230		
GCR2 - Well 483	3/10/2011	230		
GCR2 - Well 484	8/2/2011	230		
GCR2 - Well 485	1/22/2011	230		
GCR2 - Well 486	6/6/2011	230		
GCR2 - Well 487	2/8/2011	230		



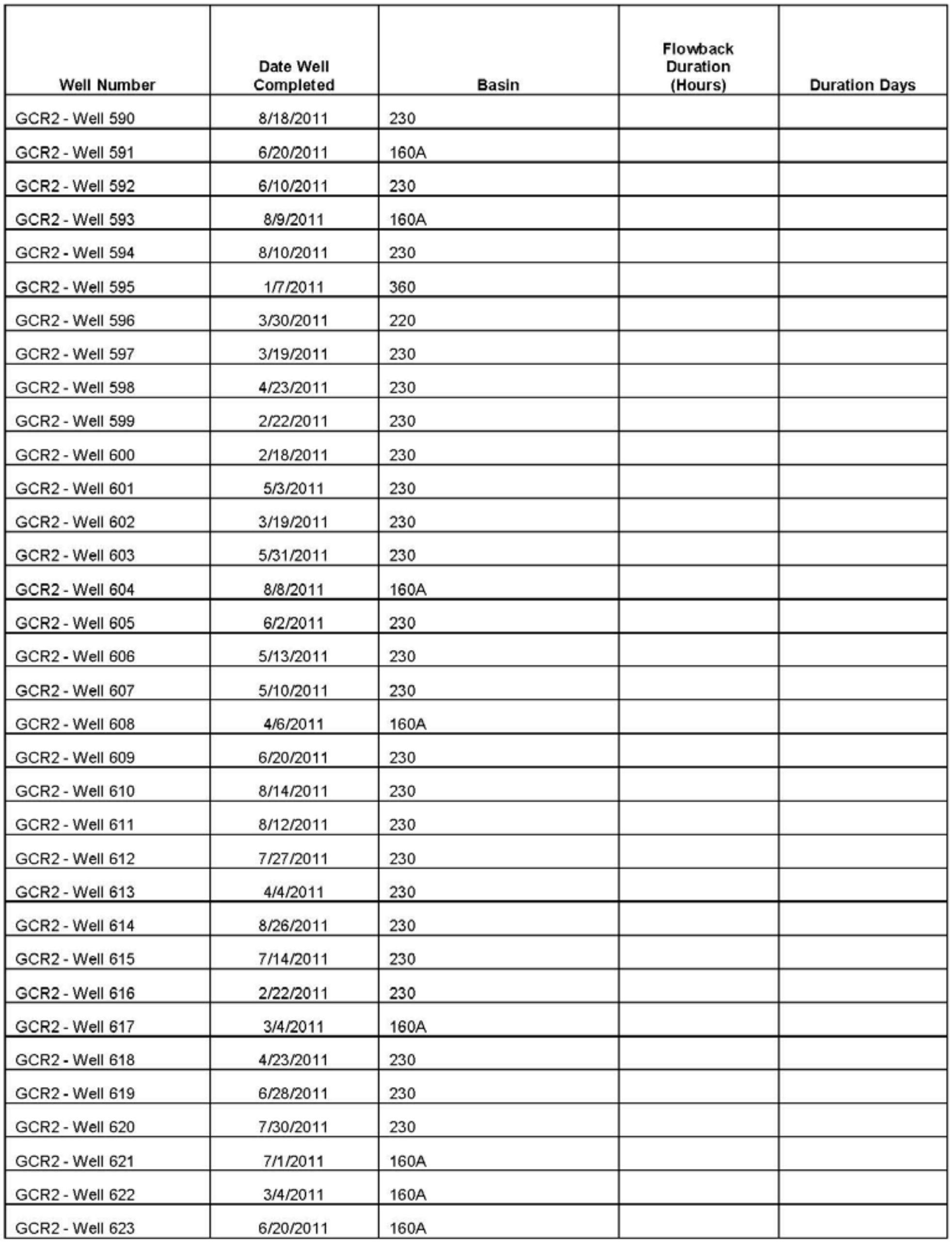
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 488	6/25/2011	160A		
GCR2 - Well 489	7/15/2011	230		
GCR2 - Well 490	1/17/2011	230		
GCR2 - Well 491	2/25/2011	230		
GCR2 - Well 492	4/16/2011	230		
GCR2 - Well 493	8/10/2011	230		
GCR2 - Well 494	5/24/2011	160A	178	
GCR2 - Well 495	7/28/2011	415		
GCR2 - Well 496	2/27/2011	260		
GCR2 - Well 497	3/12/2011	230		
GCR2 - Well 498	8/12/2011	230		
GCR2 - Well 499	5/28/2011	230		
GCR2 - Well 500	6/21/2011	230		
GCR2 - Well 501	4/8/2011	230		
GCR2 - Well 502	1/7/2011	230		
GCR2 - Well 503	8/15/2011	230		
GCR2 - Well 504	6/6/2011	230		
GCR2 - Well 505	3/18/2011	230		
GCR2 - Well 506	2/23/2011	415		
GCR2 - Well 507	3/1/2011	415		
GCR2 - Well 508	1/3/2011	230		
GCR2 - Well 509	4/27/2011	230		
GCR2 - Well 510	7/2/2011	160A		
GCR2 - Well 511	7/28/2011	415		
GCR2 - Well 512	1/12/2011	230		
GCR2 - Well 513	7/15/2011	230		
GCR2 - Well 514	3/17/2011	230		
GCR2 - Well 515	7/27/2011	230		
GCR2 - Well 516	3/15/2011	230		
GCR2 - Well 517	3/2/2011	415		
GCR2 - Well 518	1/8/2011	230		
GCR2 - Well 519	7/6/2011	230		
GCR2 - Well 520	6/25/2011	230		
GCR2 - Well 521	7/22/2011	160A		



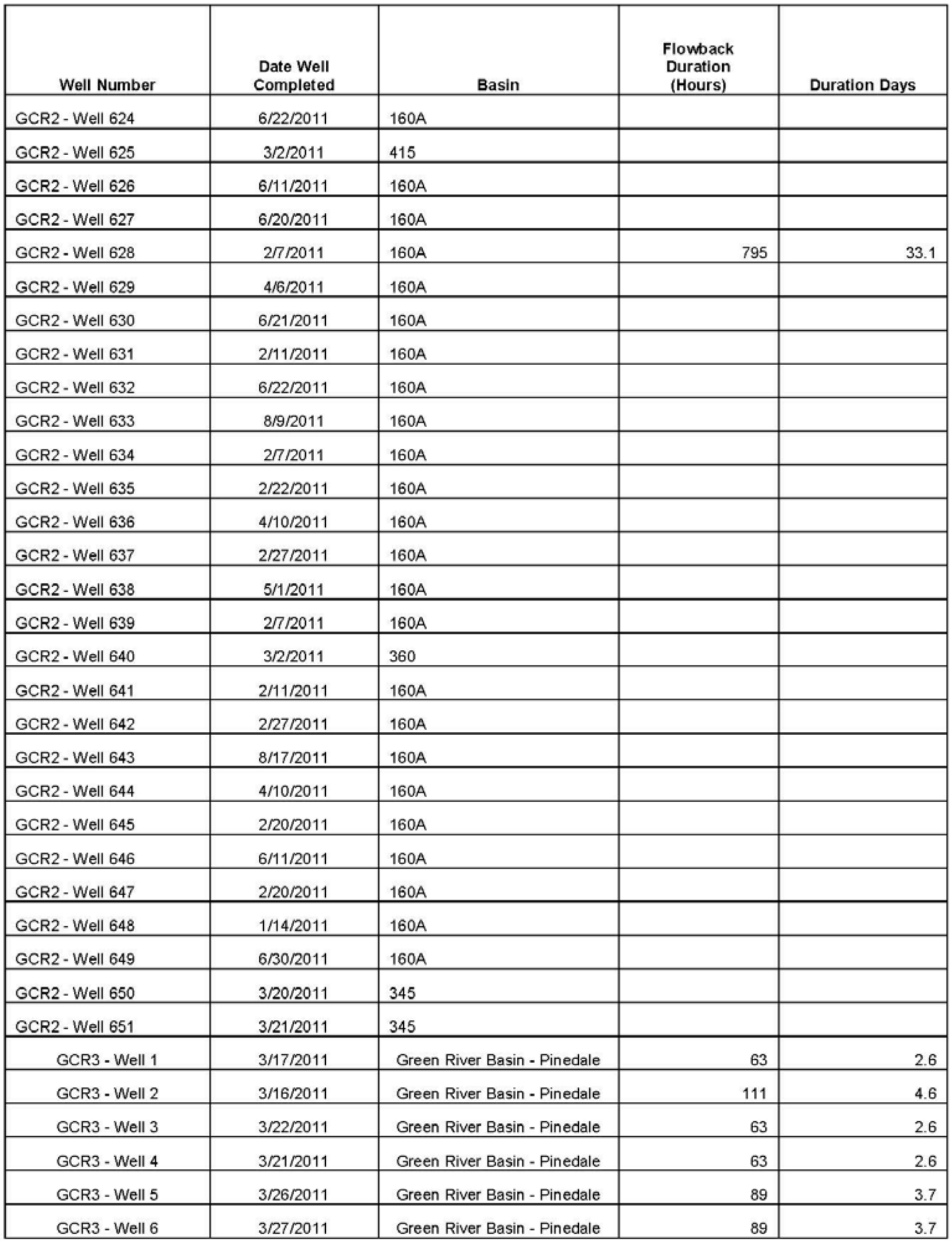
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 522	7/21/2011	160A	139	
GCR2 - Well 523	6/24/2011	230		
GCR2 - Well 524	8/9/2011	230		
GCR2 - Well 525	5/5/2011	230		
GCR2 - Well 526	1/21/2011	230		
GCR2 - Well 527	8/16/2011	230		
GCR2 - Well 528	8/3/2011	230		
GCR2 - Well 529	4/13/2011	230		
GCR2 - Well 530	7/29/2011	230		
GCR2 - Well 531	7/28/2011	230		
GCR2 - Well 532	4/9/2011	230		
GCR2 - Well 533	3/18/2011	260		
GCR2 - Well 534	6/13/2011	260		
GCR2 - Well 535	1/8/2011	230		
GCR2 - Well 536	1/31/2011	230		
GCR2 - Well 537	3/23/2011	230		
GCR2 - Well 538	5/19/2011	230		
GCR2 - Well 539	4/4/2011	230		
GCR2 - Well 540	7/14/2011	415		
GCR2 - Well 541	8/1/2011	230		
GCR2 - Well 542	1/27/2011	230		
GCR2 - Well 543	6/17/2011	260		
GCR2 - Well 544	5/31/2011	230		
GCR2 - Well 545	6/29/2011	230		
GCR2 - Well 546	8/29/2011	260		
GCR2 - Well 547	5/14/2011	230		
GCR2 - Well 548	8/27/2011	230		
GCR2 - Well 549	6/9/2011	230		
GCR2 - Well 550	6/24/2011	230		
GCR2 - Well 551	3/4/2011	230		
GCR2 - Well 552	3/2/2011	415		
GCR2 - Well 553	8/31/2011	160A		
GCR2 - Well 554	3/26/2011	415		
GCR2 - Well 555	6/1/2011	230		



Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 556	8/25/2011	415		
GCR2 - Well 557	8/12/2011	230		
GCR2 - Well 558	8/8/2011	160A		
GCR2 - Well 559	3/26/2011	415		
GCR2 - Well 560	8/10/2011	230		
GCR2 - Well 561	8/8/2011	160A		
GCR2 - Well 562	8/12/2011	230		
GCR2 - Well 563	2/26/2011	230		
GCR2 - Well 564	8/8/2011	160A		
GCR2 - Well 565	1/21/2011	230		
GCR2 - Well 566	7/5/2011	230		
GCR2 - Well 567	5/17/2011	230		
GCR2 - Well 568	4/30/2011	230		
GCR2 - Well 569	2/25/2011	230		
GCR2 - Well 570	2/9/2011	230		
GCR2 - Well 571	7/12/2011	230		
GCR2 - Well 572	7/1/2011	230	139	5.8
GCR2 - Well 573	8/15/2011	230		
GCR2 - Well 574	1/12/2011	230		
GCR2 - Well 575	8/4/2011	230		
GCR2 - Well 576	7/15/2011	230		
GCR2 - Well 577	8/13/2011	230		
GCR2 - Well 578	8/29/2011	230		
GCR2 - Well 579	7/6/2011	230		
GCR2 - Well 580	8/29/2011	230		
GCR2 - Well 581	8/18/2011	230		
GCR2 - Well 582	7/19/2011	230		
GCR2 - Well 583	8/24/2011	230		
GCR2 - Well 584	7/11/2011	230		
GCR2 - Well 585	7/22/2011	230		
GCR2 - Well 586	1/18/2011	230		
GCR2 - Well 587	8/10/2011	230		
GCR2 - Well 588	8/30/2011	230		
GCR2 - Well 589	2/24/2011	230		

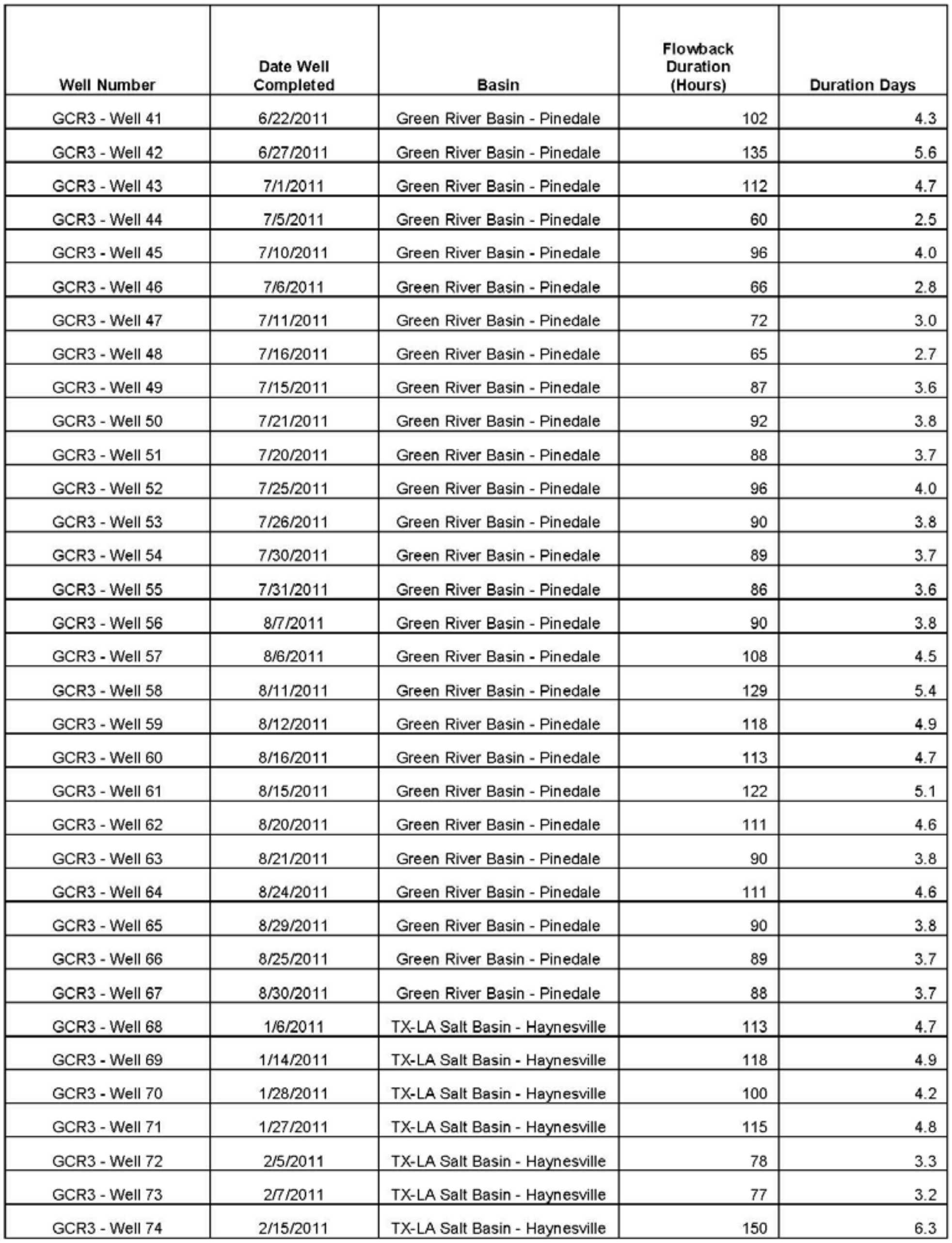


Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 590	8/18/2011	230		
GCR2 - Well 591	6/20/2011	160A		
GCR2 - Well 592	6/10/2011	230		
GCR2 - Well 593	8/9/2011	160A		
GCR2 - Well 594	8/10/2011	230		
GCR2 - Well 595	1/7/2011	360		
GCR2 - Well 596	3/30/2011	220		
GCR2 - Well 597	3/19/2011	230		
GCR2 - Well 598	4/23/2011	230		
GCR2 - Well 599	2/22/2011	230		
GCR2 - Well 600	2/18/2011	230		
GCR2 - Well 601	5/3/2011	230		
GCR2 - Well 602	3/19/2011	230		
GCR2 - Well 603	5/31/2011	230		
GCR2 - Well 604	8/8/2011	160A		
GCR2 - Well 605	6/2/2011	230		
GCR2 - Well 606	5/13/2011	230		
GCR2 - Well 607	5/10/2011	230		
GCR2 - Well 608	4/6/2011	160A		
GCR2 - Well 609	6/20/2011	230		
GCR2 - Well 610	8/14/2011	230		
GCR2 - Well 611	8/12/2011	230		
GCR2 - Well 612	7/27/2011	230		
GCR2 - Well 613	4/4/2011	230		
GCR2 - Well 614	8/26/2011	230		
GCR2 - Well 615	7/14/2011	230		
GCR2 - Well 616	2/22/2011	230		
GCR2 - Well 617	3/4/2011	160A		
GCR2 - Well 618	4/23/2011	230		
GCR2 - Well 619	6/28/2011	230		
GCR2 - Well 620	7/30/2011	230		
GCR2 - Well 621	7/1/2011	160A		
GCR2 - Well 622	3/4/2011	160A		
GCR2 - Well 623	6/20/2011	160A		

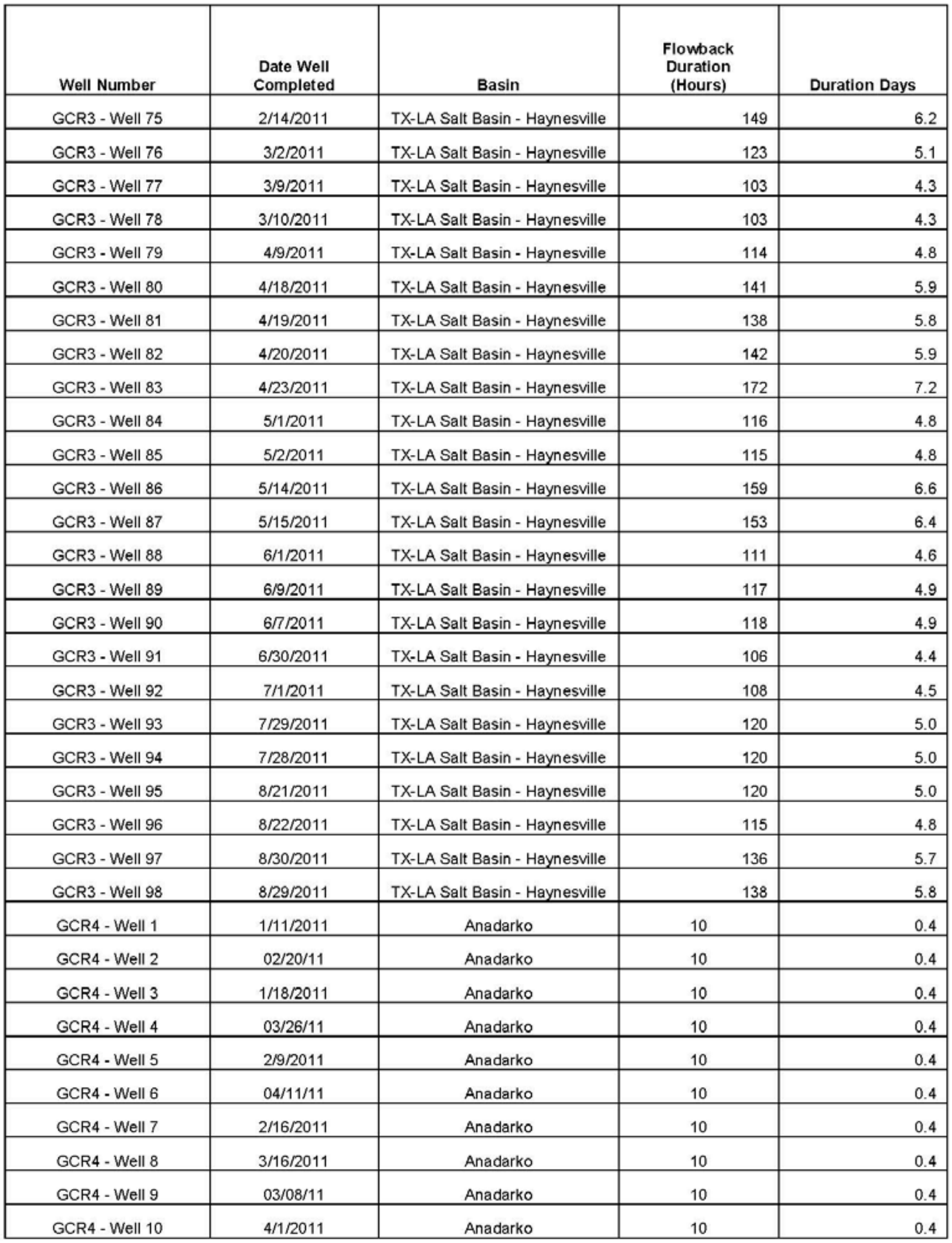


Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR2 - Well 624	6/22/2011	160A		
GCR2 - Well 625	3/2/2011	415		
GCR2 - Well 626	6/11/2011	160A		
GCR2 - Well 627	6/20/2011	160A		
GCR2 - Well 628	2/7/2011	160A	795	33.1
GCR2 - Well 629	4/6/2011	160A		
GCR2 - Well 630	6/21/2011	160A		
GCR2 - Well 631	2/11/2011	160A		
GCR2 - Well 632	6/22/2011	160A		
GCR2 - Well 633	8/9/2011	160A		
GCR2 - Well 634	2/7/2011	160A		
GCR2 - Well 635	2/22/2011	160A		
GCR2 - Well 636	4/10/2011	160A		
GCR2 - Well 637	2/27/2011	160A		
GCR2 - Well 638	5/1/2011	160A		
GCR2 - Well 639	2/7/2011	160A		
GCR2 - Well 640	3/2/2011	360		
GCR2 - Well 641	2/11/2011	160A		
GCR2 - Well 642	2/27/2011	160A		
GCR2 - Well 643	8/17/2011	160A		
GCR2 - Well 644	4/10/2011	160A		
GCR2 - Well 645	2/20/2011	160A		
GCR2 - Well 646	6/11/2011	160A		
GCR2 - Well 647	2/20/2011	160A		
GCR2 - Well 648	1/14/2011	160A		
GCR2 - Well 649	6/30/2011	160A		
GCR2 - Well 650	3/20/2011	345		
GCR2 - Well 651	3/21/2011	345		
GCR3 - Well 1	3/17/2011	Green River Basin - Pinedale	63	2.6
GCR3 - Well 2	3/16/2011	Green River Basin - Pinedale	111	4.6
GCR3 - Well 3	3/22/2011	Green River Basin - Pinedale	63	2.6
GCR3 - Well 4	3/21/2011	Green River Basin - Pinedale	63	2.6
GCR3 - Well 5	3/26/2011	Green River Basin - Pinedale	89	3.7
GCR3 - Well 6	3/27/2011	Green River Basin - Pinedale	89	3.7

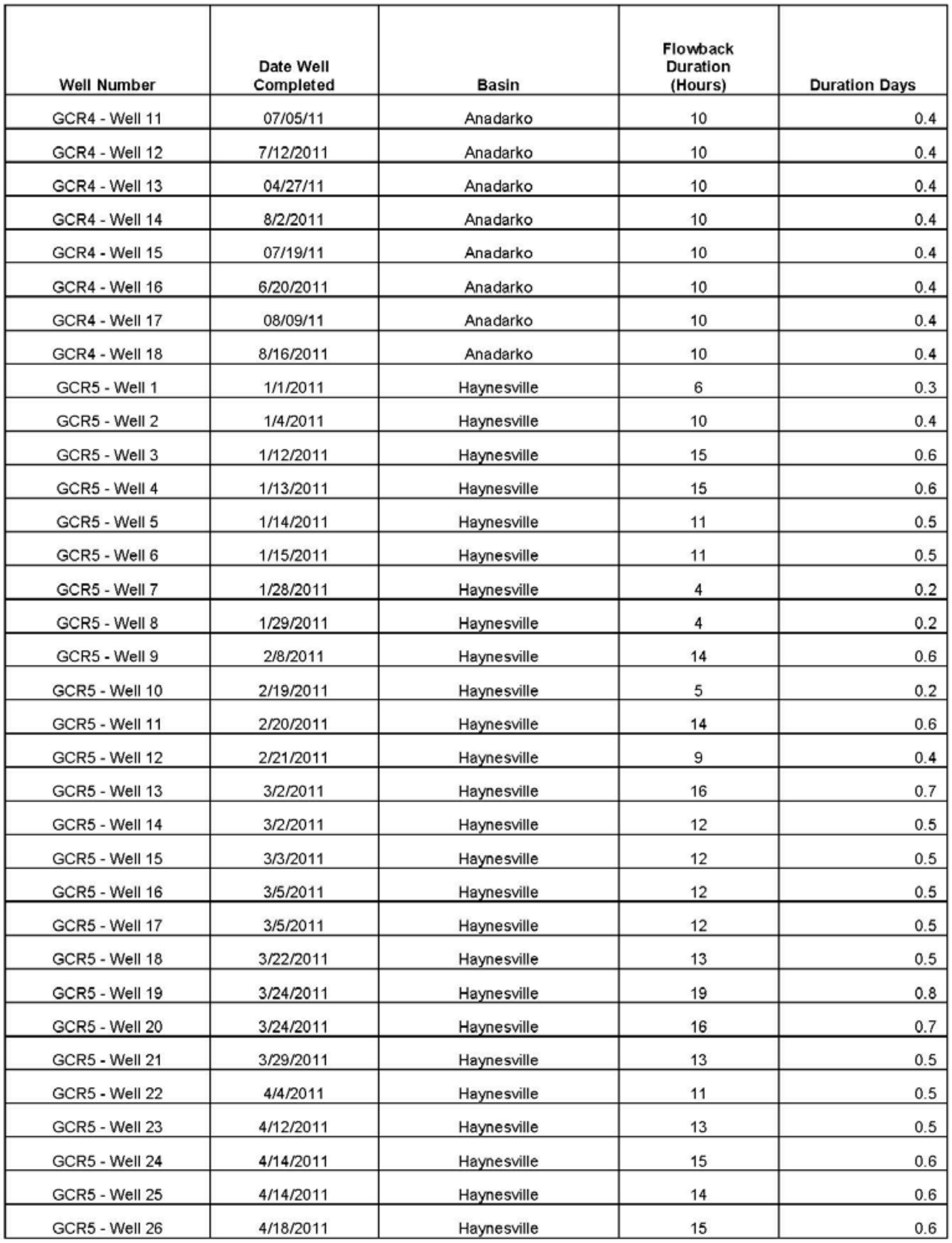
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR3 - Well 7	4/7/2011	Green River Basin - Pinedale	46	1.9
GCR3 - Well 8	4/2/2011	Green River Basin - Pinedale	55	2.3
GCR3 - Well 9	4/6/2011	Green River Basin - Pinedale	72	3.0
GCR3 - Well 10	4/1/2011	Green River Basin - Pinedale	65	2.7
GCR3 - Well 11	4/11/2011	Green River Basin - Pinedale	109	4.5
GCR3 - Well 12	4/12/2011	Green River Basin - Pinedale	111	4.6
GCR3 - Well 13	4/16/2011	Green River Basin - Pinedale	108	4.5
GCR3 - Well 14	4/17/2011	Green River Basin - Pinedale	111	4.6
GCR3 - Well 15	4/22/2011	Green River Basin - Pinedale	113	4.7
GCR3 - Well 16	4/21/2011	Green River Basin - Pinedale	86	3.6
GCR3 - Well 17	4/26/2011	Green River Basin - Pinedale	132	5.5
GCR3 - Well 18	5/1/2011	Green River Basin - Pinedale	89	3.7
GCR3 - Well 19	4/27/2011	Green River Basin - Pinedale	87	3.6
GCR3 - Well 20	5/2/2011	Green River Basin - Pinedale	86	3.6
GCR3 - Well 21	5/6/2011	Green River Basin - Pinedale	87	3.6
GCR3 - Well 22	5/7/2011	Green River Basin - Pinedale	92	3.8
GCR3 - Well 23	5/11/2011	Green River Basin - Pinedale	89	3.7
GCR3 - Well 24	5/12/2011	Green River Basin - Pinedale	67	2.8
GCR3 - Well 25	5/16/2011	Green River Basin - Pinedale	81	3.4
GCR3 - Well 26	5/17/2011	Green River Basin - Pinedale	94	3.9
GCR3 - Well 27	5/21/2011	Green River Basin - Pinedale	74	3.1
GCR3 - Well 28	5/22/2011	Green River Basin - Pinedale	88	3.7
GCR3 - Well 29	5/27/2011	Green River Basin - Pinedale	81	3.4
GCR3 - Well 30	5/26/2011	Green River Basin - Pinedale	109	4.5
GCR3 - Well 31	5/31/2011	Green River Basin - Pinedale	101	4.2
GCR3 - Well 32	5/31/2011	Green River Basin - Pinedale	64	2.7
GCR3 - Well 33	6/6/2011	Green River Basin - Pinedale	101	4.2
GCR3 - Well 34	6/5/2011	Green River Basin - Pinedale	110	4.6
GCR3 - Well 35	6/10/2011	Green River Basin - Pinedale	111	4.6
GCR3 - Well 36	6/16/2011	Green River Basin - Pinedale	88	3.7
GCR3 - Well 37	6/11/2011	Green River Basin - Pinedale	85	3.5
GCR3 - Well 38	6/17/2011	Green River Basin - Pinedale	68	2.8
GCR3 - Well 39	6/21/2011	Green River Basin - Pinedale	132	5.5
GCR3 - Well 40	6/26/2011	Green River Basin - Pinedale	153	6.4



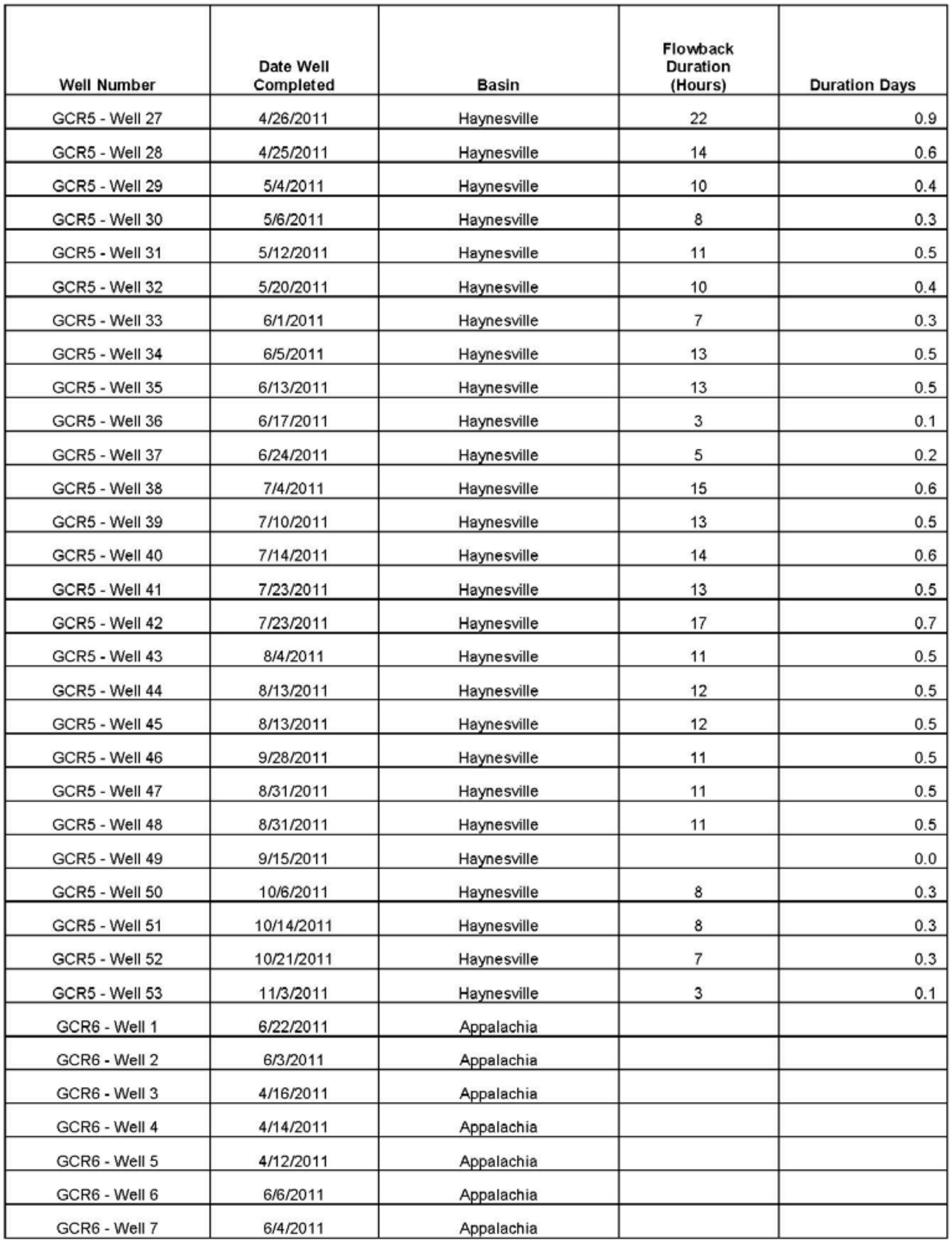
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR3 - Well 41	6/22/2011	Green River Basin - Pinedale	102	4.3
GCR3 - Well 42	6/27/2011	Green River Basin - Pinedale	135	5.6
GCR3 - Well 43	7/1/2011	Green River Basin - Pinedale	112	4.7
GCR3 - Well 44	7/5/2011	Green River Basin - Pinedale	60	2.5
GCR3 - Well 45	7/10/2011	Green River Basin - Pinedale	96	4.0
GCR3 - Well 46	7/6/2011	Green River Basin - Pinedale	66	2.8
GCR3 - Well 47	7/11/2011	Green River Basin - Pinedale	72	3.0
GCR3 - Well 48	7/16/2011	Green River Basin - Pinedale	65	2.7
GCR3 - Well 49	7/15/2011	Green River Basin - Pinedale	87	3.6
GCR3 - Well 50	7/21/2011	Green River Basin - Pinedale	92	3.8
GCR3 - Well 51	7/20/2011	Green River Basin - Pinedale	88	3.7
GCR3 - Well 52	7/25/2011	Green River Basin - Pinedale	96	4.0
GCR3 - Well 53	7/26/2011	Green River Basin - Pinedale	90	3.8
GCR3 - Well 54	7/30/2011	Green River Basin - Pinedale	89	3.7
GCR3 - Well 55	7/31/2011	Green River Basin - Pinedale	86	3.6
GCR3 - Well 56	8/7/2011	Green River Basin - Pinedale	90	3.8
GCR3 - Well 57	8/6/2011	Green River Basin - Pinedale	108	4.5
GCR3 - Well 58	8/11/2011	Green River Basin - Pinedale	129	5.4
GCR3 - Well 59	8/12/2011	Green River Basin - Pinedale	118	4.9
GCR3 - Well 60	8/16/2011	Green River Basin - Pinedale	113	4.7
GCR3 - Well 61	8/15/2011	Green River Basin - Pinedale	122	5.1
GCR3 - Well 62	8/20/2011	Green River Basin - Pinedale	111	4.6
GCR3 - Well 63	8/21/2011	Green River Basin - Pinedale	90	3.8
GCR3 - Well 64	8/24/2011	Green River Basin - Pinedale	111	4.6
GCR3 - Well 65	8/29/2011	Green River Basin - Pinedale	90	3.8
GCR3 - Well 66	8/25/2011	Green River Basin - Pinedale	89	3.7
GCR3 - Well 67	8/30/2011	Green River Basin - Pinedale	88	3.7
GCR3 - Well 68	1/6/2011	TX-LA Salt Basin - Haynesville	113	4.7
GCR3 - Well 69	1/14/2011	TX-LA Salt Basin - Haynesville	118	4.9
GCR3 - Well 70	1/28/2011	TX-LA Salt Basin - Haynesville	100	4.2
GCR3 - Well 71	1/27/2011	TX-LA Salt Basin - Haynesville	115	4.8
GCR3 - Well 72	2/5/2011	TX-LA Salt Basin - Haynesville	78	3.3
GCR3 - Well 73	2/7/2011	TX-LA Salt Basin - Haynesville	77	3.2
GCR3 - Well 74	2/15/2011	TX-LA Salt Basin - Haynesville	150	6.3



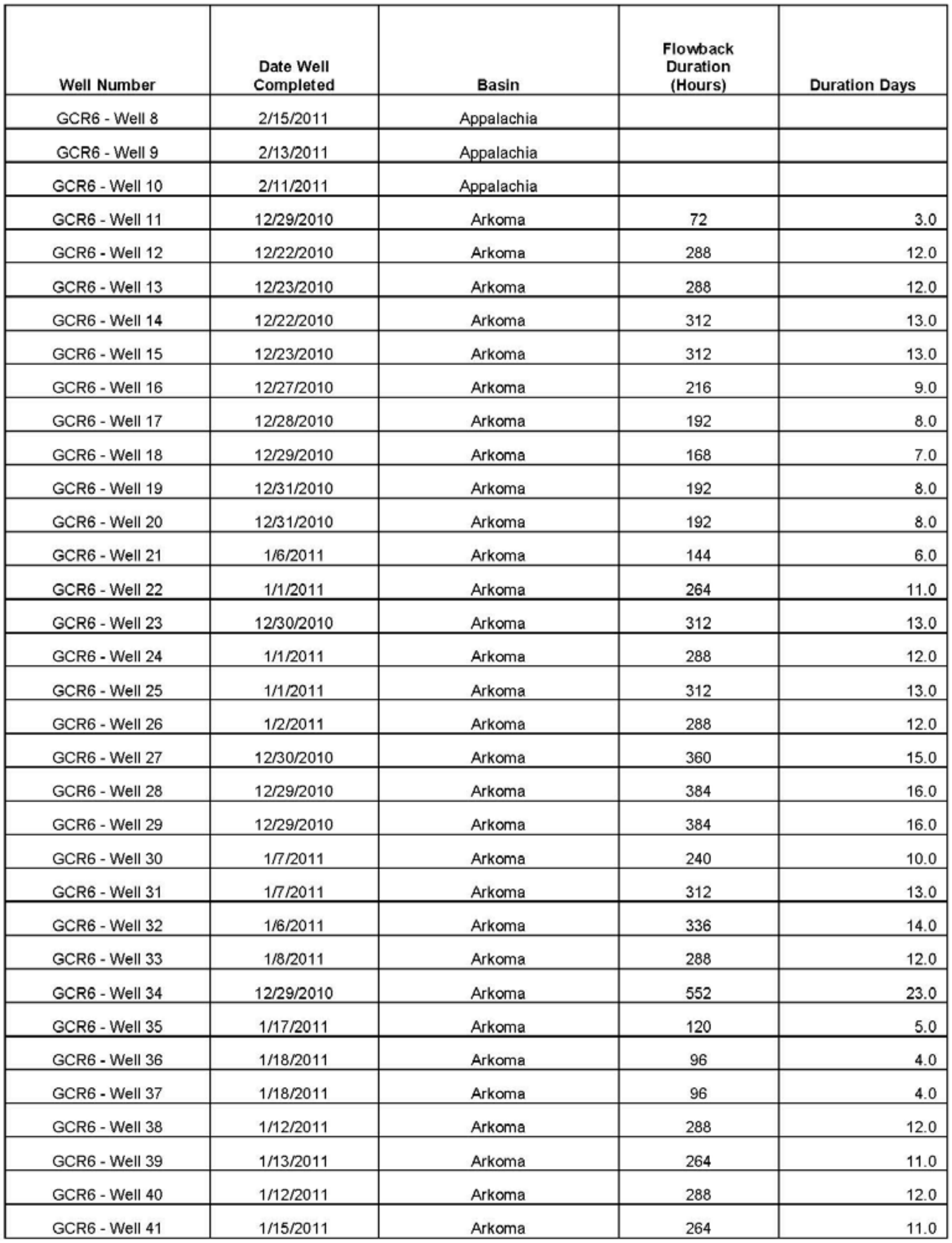
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR3 - Well 75	2/14/2011	TX-LA Salt Basin - Haynesville	149	6.2
GCR3 - Well 76	3/2/2011	TX-LA Salt Basin - Haynesville	123	5.1
GCR3 - Well 77	3/9/2011	TX-LA Salt Basin - Haynesville	103	4.3
GCR3 - Well 78	3/10/2011	TX-LA Salt Basin - Haynesville	103	4.3
GCR3 - Well 79	4/9/2011	TX-LA Salt Basin - Haynesville	114	4.8
GCR3 - Well 80	4/18/2011	TX-LA Salt Basin - Haynesville	141	5.9
GCR3 - Well 81	4/19/2011	TX-LA Salt Basin - Haynesville	138	5.8
GCR3 - Well 82	4/20/2011	TX-LA Salt Basin - Haynesville	142	5.9
GCR3 - Well 83	4/23/2011	TX-LA Salt Basin - Haynesville	172	7.2
GCR3 - Well 84	5/1/2011	TX-LA Salt Basin - Haynesville	116	4.8
GCR3 - Well 85	5/2/2011	TX-LA Salt Basin - Haynesville	115	4.8
GCR3 - Well 86	5/14/2011	TX-LA Salt Basin - Haynesville	159	6.6
GCR3 - Well 87	5/15/2011	TX-LA Salt Basin - Haynesville	153	6.4
GCR3 - Well 88	6/1/2011	TX-LA Salt Basin - Haynesville	111	4.6
GCR3 - Well 89	6/9/2011	TX-LA Salt Basin - Haynesville	117	4.9
GCR3 - Well 90	6/7/2011	TX-LA Salt Basin - Haynesville	118	4.9
GCR3 - Well 91	6/30/2011	TX-LA Salt Basin - Haynesville	106	4.4
GCR3 - Well 92	7/1/2011	TX-LA Salt Basin - Haynesville	108	4.5
GCR3 - Well 93	7/29/2011	TX-LA Salt Basin - Haynesville	120	5.0
GCR3 - Well 94	7/28/2011	TX-LA Salt Basin - Haynesville	120	5.0
GCR3 - Well 95	8/21/2011	TX-LA Salt Basin - Haynesville	120	5.0
GCR3 - Well 96	8/22/2011	TX-LA Salt Basin - Haynesville	115	4.8
GCR3 - Well 97	8/30/2011	TX-LA Salt Basin - Haynesville	136	5.7
GCR3 - Well 98	8/29/2011	TX-LA Salt Basin - Haynesville	138	5.8
GCR4 - Well 1	1/11/2011	Anadarko	10	0.4
GCR4 - Well 2	02/20/11	Anadarko	10	0.4
GCR4 - Well 3	1/18/2011	Anadarko	10	0.4
GCR4 - Well 4	03/26/11	Anadarko	10	0.4
GCR4 - Well 5	2/9/2011	Anadarko	10	0.4
GCR4 - Well 6	04/11/11	Anadarko	10	0.4
GCR4 - Well 7	2/16/2011	Anadarko	10	0.4
GCR4 - Well 8	3/16/2011	Anadarko	10	0.4
GCR4 - Well 9	03/08/11	Anadarko	10	0.4
GCR4 - Well 10	4/1/2011	Anadarko	10	0.4



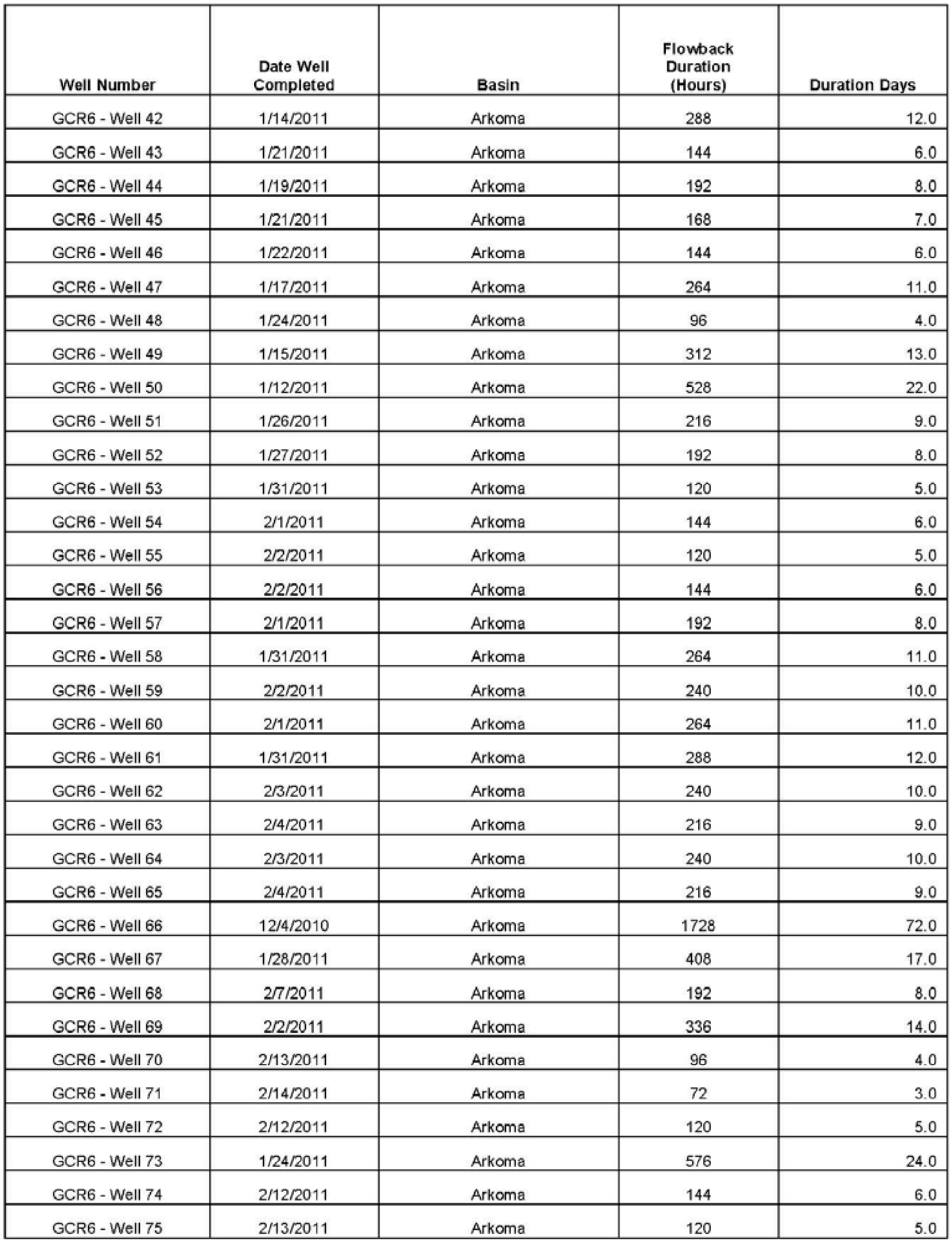
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR4 - Well 11	07/05/11	Anadarko	10	0.4
GCR4 - Well 12	7/12/2011	Anadarko	10	0.4
GCR4 - Well 13	04/27/11	Anadarko	10	0.4
GCR4 - Well 14	8/2/2011	Anadarko	10	0.4
GCR4 - Well 15	07/19/11	Anadarko	10	0.4
GCR4 - Well 16	6/20/2011	Anadarko	10	0.4
GCR4 - Well 17	08/09/11	Anadarko	10	0.4
GCR4 - Well 18	8/16/2011	Anadarko	10	0.4
GCR5 - Well 1	1/1/2011	Haynesville	6	0.3
GCR5 - Well 2	1/4/2011	Haynesville	10	0.4
GCR5 - Well 3	1/12/2011	Haynesville	15	0.6
GCR5 - Well 4	1/13/2011	Haynesville	15	0.6
GCR5 - Well 5	1/14/2011	Haynesville	11	0.5
GCR5 - Well 6	1/15/2011	Haynesville	11	0.5
GCR5 - Well 7	1/28/2011	Haynesville	4	0.2
GCR5 - Well 8	1/29/2011	Haynesville	4	0.2
GCR5 - Well 9	2/8/2011	Haynesville	14	0.6
GCR5 - Well 10	2/19/2011	Haynesville	5	0.2
GCR5 - Well 11	2/20/2011	Haynesville	14	0.6
GCR5 - Well 12	2/21/2011	Haynesville	9	0.4
GCR5 - Well 13	3/2/2011	Haynesville	16	0.7
GCR5 - Well 14	3/2/2011	Haynesville	12	0.5
GCR5 - Well 15	3/3/2011	Haynesville	12	0.5
GCR5 - Well 16	3/5/2011	Haynesville	12	0.5
GCR5 - Well 17	3/5/2011	Haynesville	12	0.5
GCR5 - Well 18	3/22/2011	Haynesville	13	0.5
GCR5 - Well 19	3/24/2011	Haynesville	19	0.8
GCR5 - Well 20	3/24/2011	Haynesville	16	0.7
GCR5 - Well 21	3/29/2011	Haynesville	13	0.5
GCR5 - Well 22	4/4/2011	Haynesville	11	0.5
GCR5 - Well 23	4/12/2011	Haynesville	13	0.5
GCR5 - Well 24	4/14/2011	Haynesville	15	0.6
GCR5 - Well 25	4/14/2011	Haynesville	14	0.6
GCR5 - Well 26	4/18/2011	Haynesville	15	0.6



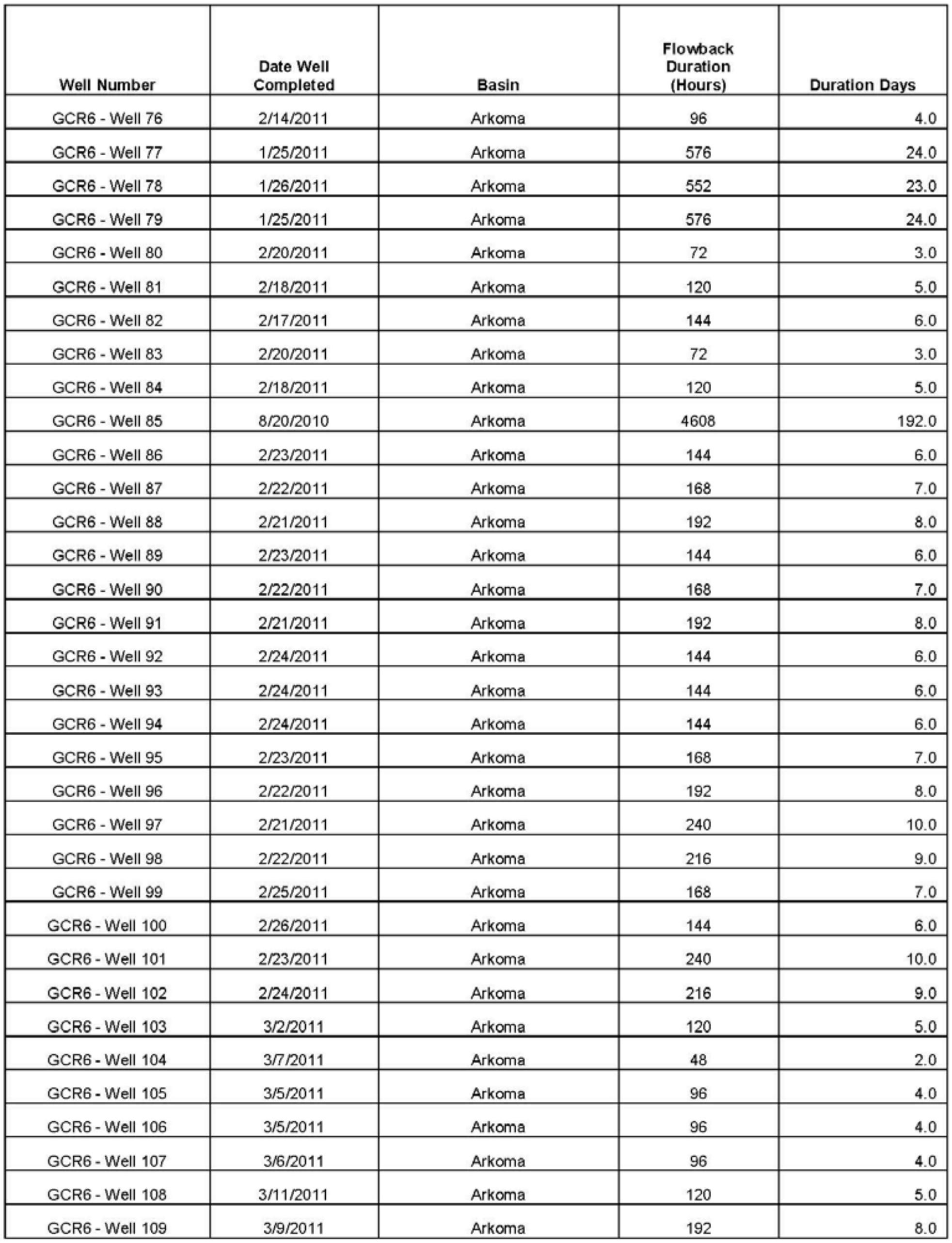
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR5 - Well 27	4/26/2011	Haynesville	22	0.9
GCR5 - Well 28	4/25/2011	Haynesville	14	0.6
GCR5 - Well 29	5/4/2011	Haynesville	10	0.4
GCR5 - Well 30	5/6/2011	Haynesville	8	0.3
GCR5 - Well 31	5/12/2011	Haynesville	11	0.5
GCR5 - Well 32	5/20/2011	Haynesville	10	0.4
GCR5 - Well 33	6/1/2011	Haynesville	7	0.3
GCR5 - Well 34	6/5/2011	Haynesville	13	0.5
GCR5 - Well 35	6/13/2011	Haynesville	13	0.5
GCR5 - Well 36	6/17/2011	Haynesville	3	0.1
GCR5 - Well 37	6/24/2011	Haynesville	5	0.2
GCR5 - Well 38	7/4/2011	Haynesville	15	0.6
GCR5 - Well 39	7/10/2011	Haynesville	13	0.5
GCR5 - Well 40	7/14/2011	Haynesville	14	0.6
GCR5 - Well 41	7/23/2011	Haynesville	13	0.5
GCR5 - Well 42	7/23/2011	Haynesville	17	0.7
GCR5 - Well 43	8/4/2011	Haynesville	11	0.5
GCR5 - Well 44	8/13/2011	Haynesville	12	0.5
GCR5 - Well 45	8/13/2011	Haynesville	12	0.5
GCR5 - Well 46	9/28/2011	Haynesville	11	0.5
GCR5 - Well 47	8/31/2011	Haynesville	11	0.5
GCR5 - Well 48	8/31/2011	Haynesville	11	0.5
GCR5 - Well 49	9/15/2011	Haynesville		0.0
GCR5 - Well 50	10/6/2011	Haynesville	8	0.3
GCR5 - Well 51	10/14/2011	Haynesville	8	0.3
GCR5 - Well 52	10/21/2011	Haynesville	7	0.3
GCR5 - Well 53	11/3/2011	Haynesville	3	0.1
GCR6 - Well 1	6/22/2011	Appalachia		
GCR6 - Well 2	6/3/2011	Appalachia		
GCR6 - Well 3	4/16/2011	Appalachia		
GCR6 - Well 4	4/14/2011	Appalachia		
GCR6 - Well 5	4/12/2011	Appalachia		
GCR6 - Well 6	6/6/2011	Appalachia		
GCR6 - Well 7	6/4/2011	Appalachia		



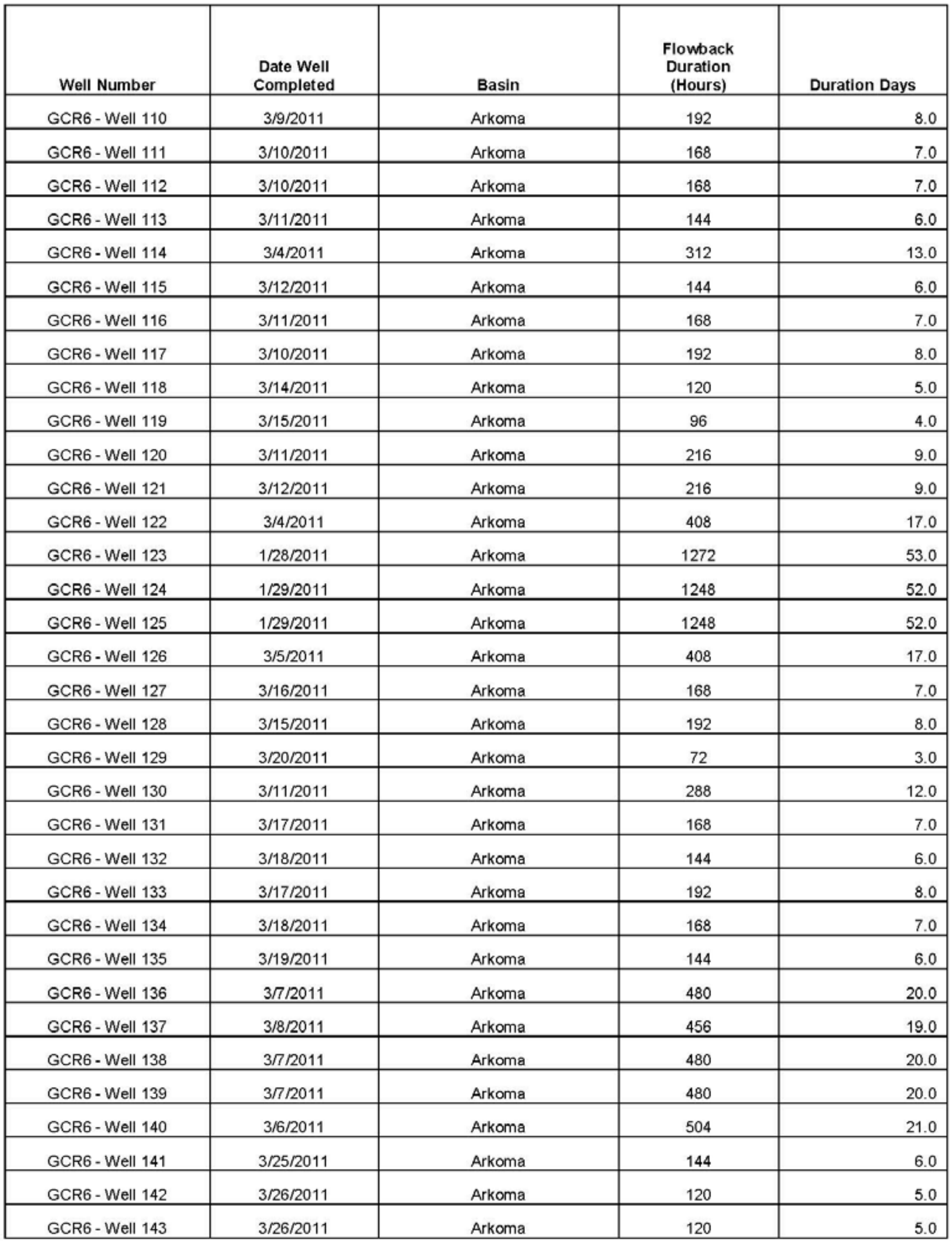
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 8	2/15/2011	Appalachia		
GCR6 - Well 9	2/13/2011	Appalachia		
GCR6 - Well 10	2/11/2011	Appalachia		
GCR6 - Well 11	12/29/2010	Arkoma	72	3.0
GCR6 - Well 12	12/22/2010	Arkoma	288	12.0
GCR6 - Well 13	12/23/2010	Arkoma	288	12.0
GCR6 - Well 14	12/22/2010	Arkoma	312	13.0
GCR6 - Well 15	12/23/2010	Arkoma	312	13.0
GCR6 - Well 16	12/27/2010	Arkoma	216	9.0
GCR6 - Well 17	12/28/2010	Arkoma	192	8.0
GCR6 - Well 18	12/29/2010	Arkoma	168	7.0
GCR6 - Well 19	12/31/2010	Arkoma	192	8.0
GCR6 - Well 20	12/31/2010	Arkoma	192	8.0
GCR6 - Well 21	1/6/2011	Arkoma	144	6.0
GCR6 - Well 22	1/1/2011	Arkoma	264	11.0
GCR6 - Well 23	12/30/2010	Arkoma	312	13.0
GCR6 - Well 24	1/1/2011	Arkoma	288	12.0
GCR6 - Well 25	1/1/2011	Arkoma	312	13.0
GCR6 - Well 26	1/2/2011	Arkoma	288	12.0
GCR6 - Well 27	12/30/2010	Arkoma	360	15.0
GCR6 - Well 28	12/29/2010	Arkoma	384	16.0
GCR6 - Well 29	12/29/2010	Arkoma	384	16.0
GCR6 - Well 30	1/7/2011	Arkoma	240	10.0
GCR6 - Well 31	1/7/2011	Arkoma	312	13.0
GCR6 - Well 32	1/6/2011	Arkoma	336	14.0
GCR6 - Well 33	1/8/2011	Arkoma	288	12.0
GCR6 - Well 34	12/29/2010	Arkoma	552	23.0
GCR6 - Well 35	1/17/2011	Arkoma	120	5.0
GCR6 - Well 36	1/18/2011	Arkoma	96	4.0
GCR6 - Well 37	1/18/2011	Arkoma	96	4.0
GCR6 - Well 38	1/12/2011	Arkoma	288	12.0
GCR6 - Well 39	1/13/2011	Arkoma	264	11.0
GCR6 - Well 40	1/12/2011	Arkoma	288	12.0
GCR6 - Well 41	1/15/2011	Arkoma	264	11.0



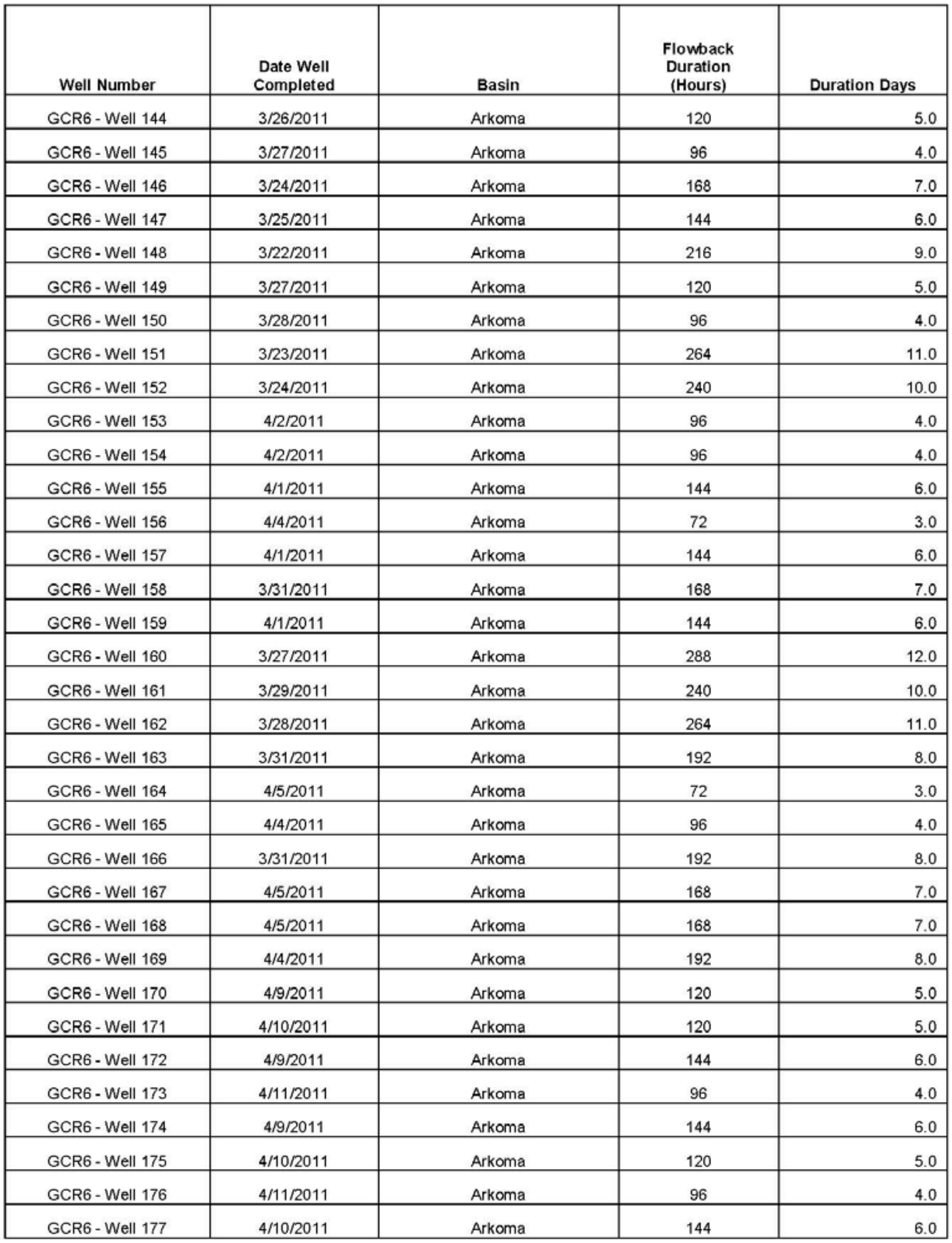
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 42	1/14/2011	Arkoma	288	12.0
GCR6 - Well 43	1/21/2011	Arkoma	144	6.0
GCR6 - Well 44	1/19/2011	Arkoma	192	8.0
GCR6 - Well 45	1/21/2011	Arkoma	168	7.0
GCR6 - Well 46	1/22/2011	Arkoma	144	6.0
GCR6 - Well 47	1/17/2011	Arkoma	264	11.0
GCR6 - Well 48	1/24/2011	Arkoma	96	4.0
GCR6 - Well 49	1/15/2011	Arkoma	312	13.0
GCR6 - Well 50	1/12/2011	Arkoma	528	22.0
GCR6 - Well 51	1/26/2011	Arkoma	216	9.0
GCR6 - Well 52	1/27/2011	Arkoma	192	8.0
GCR6 - Well 53	1/31/2011	Arkoma	120	5.0
GCR6 - Well 54	2/1/2011	Arkoma	144	6.0
GCR6 - Well 55	2/2/2011	Arkoma	120	5.0
GCR6 - Well 56	2/2/2011	Arkoma	144	6.0
GCR6 - Well 57	2/1/2011	Arkoma	192	8.0
GCR6 - Well 58	1/31/2011	Arkoma	264	11.0
GCR6 - Well 59	2/2/2011	Arkoma	240	10.0
GCR6 - Well 60	2/1/2011	Arkoma	264	11.0
GCR6 - Well 61	1/31/2011	Arkoma	288	12.0
GCR6 - Well 62	2/3/2011	Arkoma	240	10.0
GCR6 - Well 63	2/4/2011	Arkoma	216	9.0
GCR6 - Well 64	2/3/2011	Arkoma	240	10.0
GCR6 - Well 65	2/4/2011	Arkoma	216	9.0
GCR6 - Well 66	12/4/2010	Arkoma	1728	72.0
GCR6 - Well 67	1/28/2011	Arkoma	408	17.0
GCR6 - Well 68	2/7/2011	Arkoma	192	8.0
GCR6 - Well 69	2/2/2011	Arkoma	336	14.0
GCR6 - Well 70	2/13/2011	Arkoma	96	4.0
GCR6 - Well 71	2/14/2011	Arkoma	72	3.0
GCR6 - Well 72	2/12/2011	Arkoma	120	5.0
GCR6 - Well 73	1/24/2011	Arkoma	576	24.0
GCR6 - Well 74	2/12/2011	Arkoma	144	6.0
GCR6 - Well 75	2/13/2011	Arkoma	120	5.0



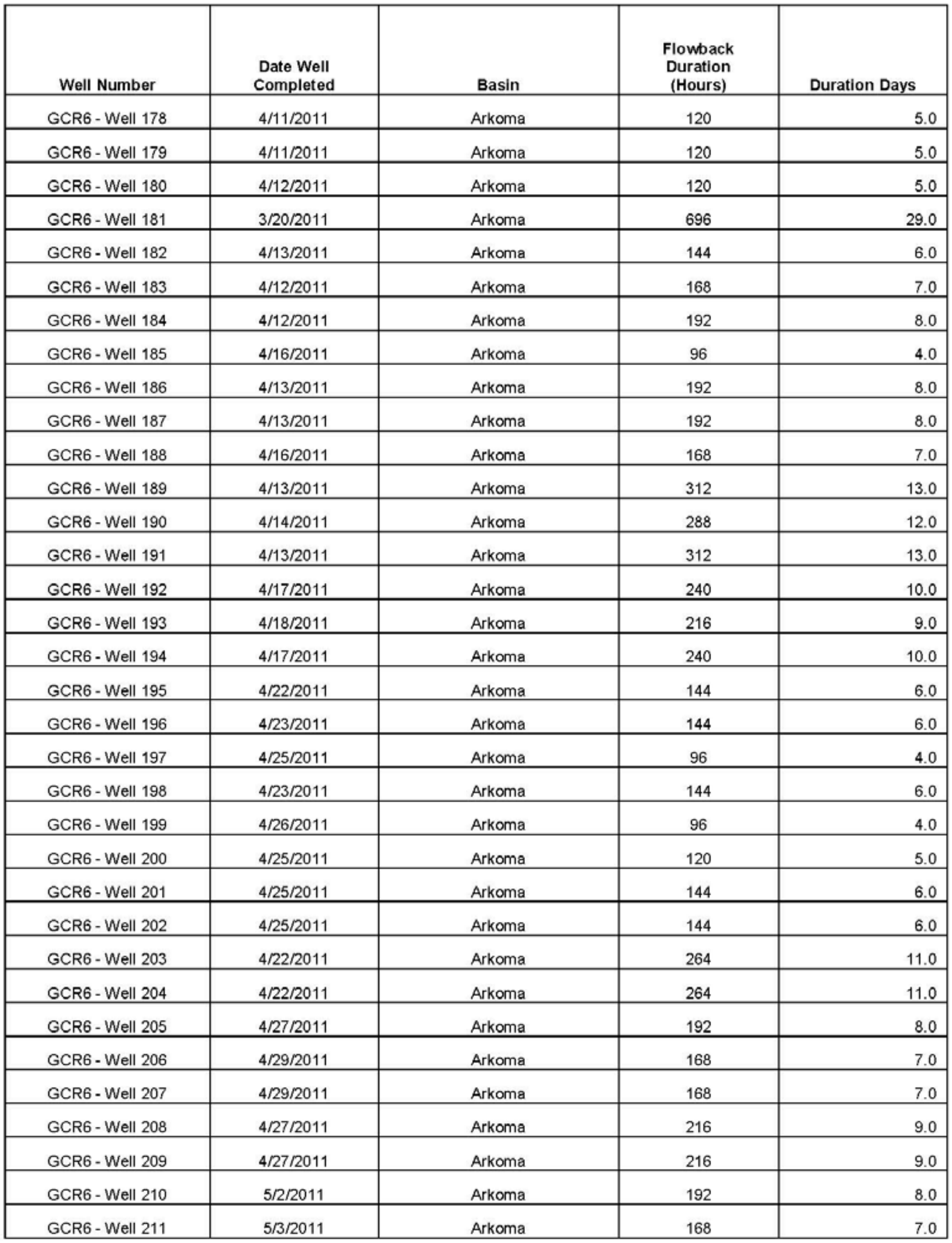
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 76	2/14/2011	Arkoma	96	4.0
GCR6 - Well 77	1/25/2011	Arkoma	576	24.0
GCR6 - Well 78	1/26/2011	Arkoma	552	23.0
GCR6 - Well 79	1/25/2011	Arkoma	576	24.0
GCR6 - Well 80	2/20/2011	Arkoma	72	3.0
GCR6 - Well 81	2/18/2011	Arkoma	120	5.0
GCR6 - Well 82	2/17/2011	Arkoma	144	6.0
GCR6 - Well 83	2/20/2011	Arkoma	72	3.0
GCR6 - Well 84	2/18/2011	Arkoma	120	5.0
GCR6 - Well 85	8/20/2010	Arkoma	4608	192.0
GCR6 - Well 86	2/23/2011	Arkoma	144	6.0
GCR6 - Well 87	2/22/2011	Arkoma	168	7.0
GCR6 - Well 88	2/21/2011	Arkoma	192	8.0
GCR6 - Well 89	2/23/2011	Arkoma	144	6.0
GCR6 - Well 90	2/22/2011	Arkoma	168	7.0
GCR6 - Well 91	2/21/2011	Arkoma	192	8.0
GCR6 - Well 92	2/24/2011	Arkoma	144	6.0
GCR6 - Well 93	2/24/2011	Arkoma	144	6.0
GCR6 - Well 94	2/24/2011	Arkoma	144	6.0
GCR6 - Well 95	2/23/2011	Arkoma	168	7.0
GCR6 - Well 96	2/22/2011	Arkoma	192	8.0
GCR6 - Well 97	2/21/2011	Arkoma	240	10.0
GCR6 - Well 98	2/22/2011	Arkoma	216	9.0
GCR6 - Well 99	2/25/2011	Arkoma	168	7.0
GCR6 - Well 100	2/26/2011	Arkoma	144	6.0
GCR6 - Well 101	2/23/2011	Arkoma	240	10.0
GCR6 - Well 102	2/24/2011	Arkoma	216	9.0
GCR6 - Well 103	3/2/2011	Arkoma	120	5.0
GCR6 - Well 104	3/7/2011	Arkoma	48	2.0
GCR6 - Well 105	3/5/2011	Arkoma	96	4.0
GCR6 - Well 106	3/5/2011	Arkoma	96	4.0
GCR6 - Well 107	3/6/2011	Arkoma	96	4.0
GCR6 - Well 108	3/11/2011	Arkoma	120	5.0
GCR6 - Well 109	3/9/2011	Arkoma	192	8.0



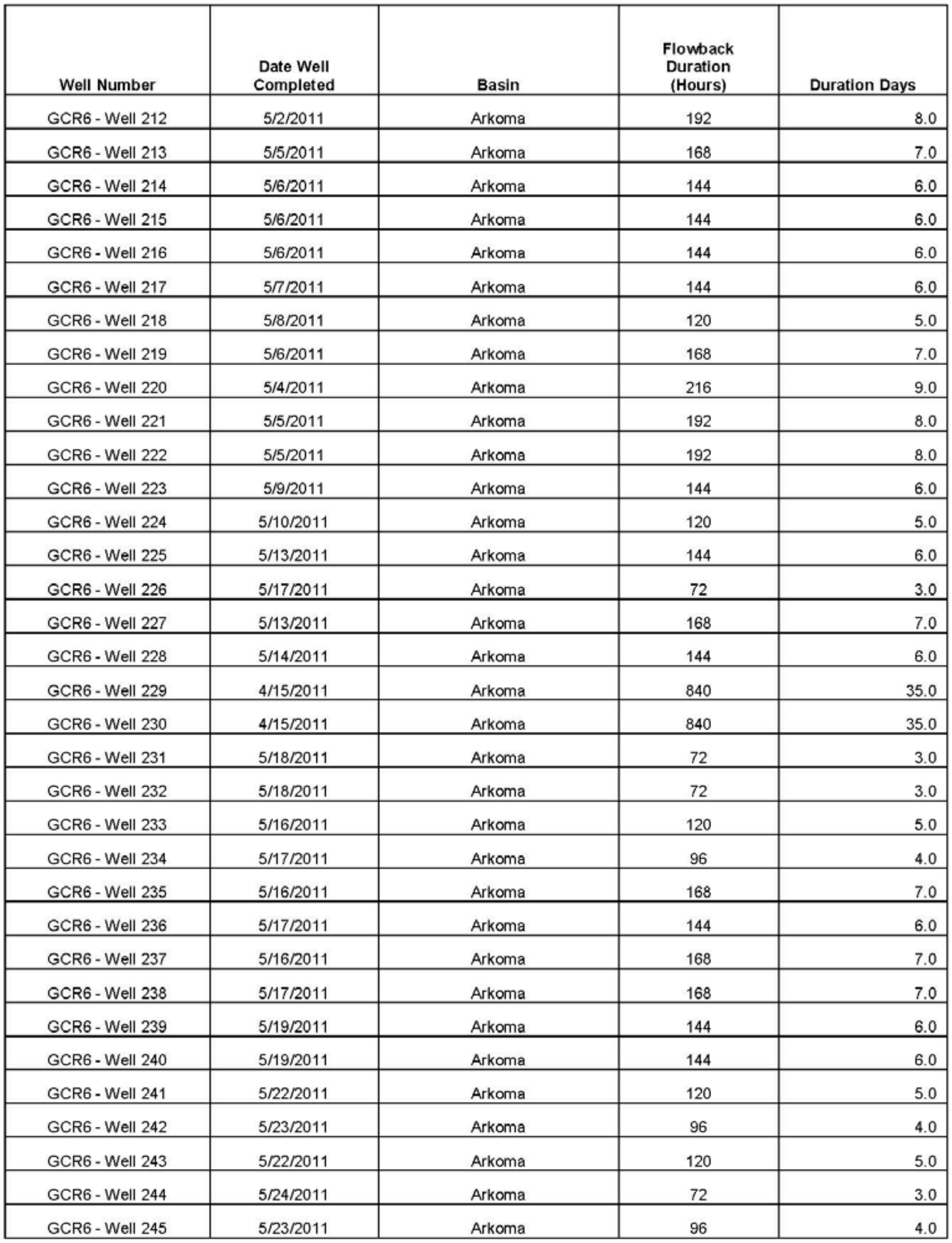
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 110	3/9/2011	Arkoma	192	8.0
GCR6 - Well 111	3/10/2011	Arkoma	168	7.0
GCR6 - Well 112	3/10/2011	Arkoma	168	7.0
GCR6 - Well 113	3/11/2011	Arkoma	144	6.0
GCR6 - Well 114	3/4/2011	Arkoma	312	13.0
GCR6 - Well 115	3/12/2011	Arkoma	144	6.0
GCR6 - Well 116	3/11/2011	Arkoma	168	7.0
GCR6 - Well 117	3/10/2011	Arkoma	192	8.0
GCR6 - Well 118	3/14/2011	Arkoma	120	5.0
GCR6 - Well 119	3/15/2011	Arkoma	96	4.0
GCR6 - Well 120	3/11/2011	Arkoma	216	9.0
GCR6 - Well 121	3/12/2011	Arkoma	216	9.0
GCR6 - Well 122	3/4/2011	Arkoma	408	17.0
GCR6 - Well 123	1/28/2011	Arkoma	1272	53.0
GCR6 - Well 124	1/29/2011	Arkoma	1248	52.0
GCR6 - Well 125	1/29/2011	Arkoma	1248	52.0
GCR6 - Well 126	3/5/2011	Arkoma	408	17.0
GCR6 - Well 127	3/16/2011	Arkoma	168	7.0
GCR6 - Well 128	3/15/2011	Arkoma	192	8.0
GCR6 - Well 129	3/20/2011	Arkoma	72	3.0
GCR6 - Well 130	3/11/2011	Arkoma	288	12.0
GCR6 - Well 131	3/17/2011	Arkoma	168	7.0
GCR6 - Well 132	3/18/2011	Arkoma	144	6.0
GCR6 - Well 133	3/17/2011	Arkoma	192	8.0
GCR6 - Well 134	3/18/2011	Arkoma	168	7.0
GCR6 - Well 135	3/19/2011	Arkoma	144	6.0
GCR6 - Well 136	3/7/2011	Arkoma	480	20.0
GCR6 - Well 137	3/8/2011	Arkoma	456	19.0
GCR6 - Well 138	3/7/2011	Arkoma	480	20.0
GCR6 - Well 139	3/7/2011	Arkoma	480	20.0
GCR6 - Well 140	3/6/2011	Arkoma	504	21.0
GCR6 - Well 141	3/25/2011	Arkoma	144	6.0
GCR6 - Well 142	3/26/2011	Arkoma	120	5.0
GCR6 - Well 143	3/26/2011	Arkoma	120	5.0



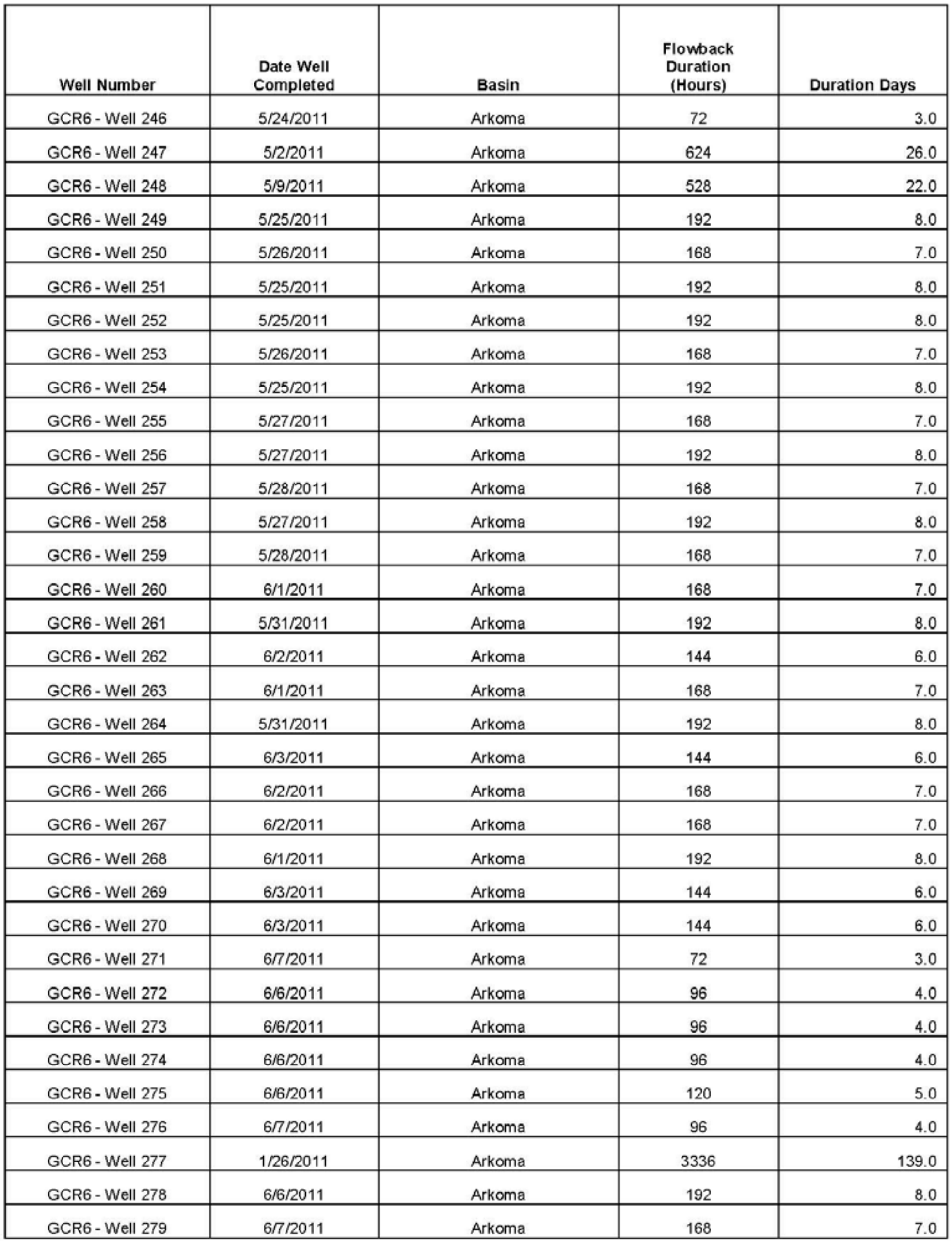
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 144	3/26/2011	Arkoma	120	5.0
GCR6 - Well 145	3/27/2011	Arkoma	96	4.0
GCR6 - Well 146	3/24/2011	Arkoma	168	7.0
GCR6 - Well 147	3/25/2011	Arkoma	144	6.0
GCR6 - Well 148	3/22/2011	Arkoma	216	9.0
GCR6 - Well 149	3/27/2011	Arkoma	120	5.0
GCR6 - Well 150	3/28/2011	Arkoma	96	4.0
GCR6 - Well 151	3/23/2011	Arkoma	264	11.0
GCR6 - Well 152	3/24/2011	Arkoma	240	10.0
GCR6 - Well 153	4/2/2011	Arkoma	96	4.0
GCR6 - Well 154	4/2/2011	Arkoma	96	4.0
GCR6 - Well 155	4/1/2011	Arkoma	144	6.0
GCR6 - Well 156	4/4/2011	Arkoma	72	3.0
GCR6 - Well 157	4/1/2011	Arkoma	144	6.0
GCR6 - Well 158	3/31/2011	Arkoma	168	7.0
GCR6 - Well 159	4/1/2011	Arkoma	144	6.0
GCR6 - Well 160	3/27/2011	Arkoma	288	12.0
GCR6 - Well 161	3/29/2011	Arkoma	240	10.0
GCR6 - Well 162	3/28/2011	Arkoma	264	11.0
GCR6 - Well 163	3/31/2011	Arkoma	192	8.0
GCR6 - Well 164	4/5/2011	Arkoma	72	3.0
GCR6 - Well 165	4/4/2011	Arkoma	96	4.0
GCR6 - Well 166	3/31/2011	Arkoma	192	8.0
GCR6 - Well 167	4/5/2011	Arkoma	168	7.0
GCR6 - Well 168	4/5/2011	Arkoma	168	7.0
GCR6 - Well 169	4/4/2011	Arkoma	192	8.0
GCR6 - Well 170	4/9/2011	Arkoma	120	5.0
GCR6 - Well 171	4/10/2011	Arkoma	120	5.0
GCR6 - Well 172	4/9/2011	Arkoma	144	6.0
GCR6 - Well 173	4/11/2011	Arkoma	96	4.0
GCR6 - Well 174	4/9/2011	Arkoma	144	6.0
GCR6 - Well 175	4/10/2011	Arkoma	120	5.0
GCR6 - Well 176	4/11/2011	Arkoma	96	4.0
GCR6 - Well 177	4/10/2011	Arkoma	144	6.0



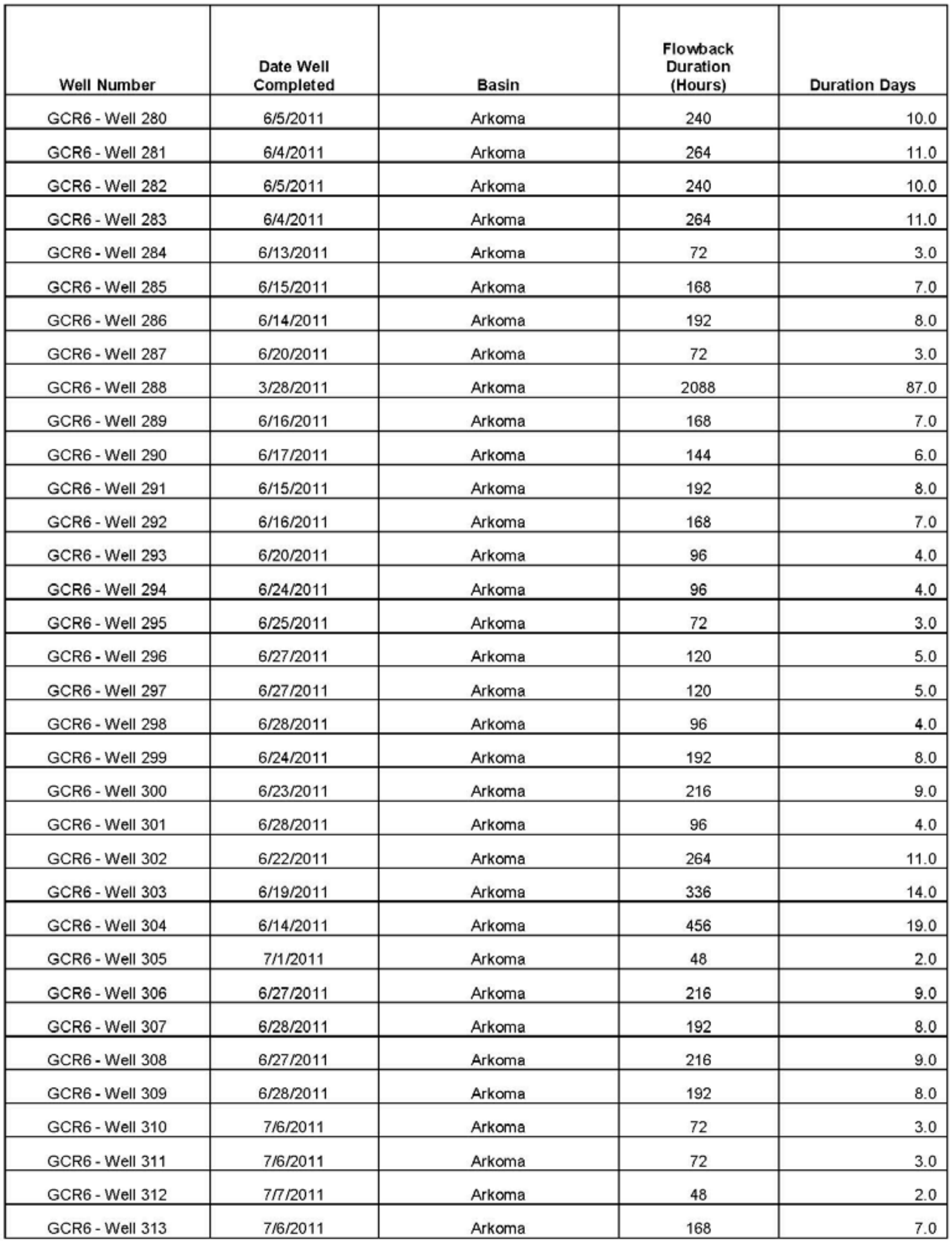
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 178	4/11/2011	Arkoma	120	5.0
GCR6 - Well 179	4/11/2011	Arkoma	120	5.0
GCR6 - Well 180	4/12/2011	Arkoma	120	5.0
GCR6 - Well 181	3/20/2011	Arkoma	696	29.0
GCR6 - Well 182	4/13/2011	Arkoma	144	6.0
GCR6 - Well 183	4/12/2011	Arkoma	168	7.0
GCR6 - Well 184	4/12/2011	Arkoma	192	8.0
GCR6 - Well 185	4/16/2011	Arkoma	96	4.0
GCR6 - Well 186	4/13/2011	Arkoma	192	8.0
GCR6 - Well 187	4/13/2011	Arkoma	192	8.0
GCR6 - Well 188	4/16/2011	Arkoma	168	7.0
GCR6 - Well 189	4/13/2011	Arkoma	312	13.0
GCR6 - Well 190	4/14/2011	Arkoma	288	12.0
GCR6 - Well 191	4/13/2011	Arkoma	312	13.0
GCR6 - Well 192	4/17/2011	Arkoma	240	10.0
GCR6 - Well 193	4/18/2011	Arkoma	216	9.0
GCR6 - Well 194	4/17/2011	Arkoma	240	10.0
GCR6 - Well 195	4/22/2011	Arkoma	144	6.0
GCR6 - Well 196	4/23/2011	Arkoma	144	6.0
GCR6 - Well 197	4/25/2011	Arkoma	96	4.0
GCR6 - Well 198	4/23/2011	Arkoma	144	6.0
GCR6 - Well 199	4/26/2011	Arkoma	96	4.0
GCR6 - Well 200	4/25/2011	Arkoma	120	5.0
GCR6 - Well 201	4/25/2011	Arkoma	144	6.0
GCR6 - Well 202	4/25/2011	Arkoma	144	6.0
GCR6 - Well 203	4/22/2011	Arkoma	264	11.0
GCR6 - Well 204	4/22/2011	Arkoma	264	11.0
GCR6 - Well 205	4/27/2011	Arkoma	192	8.0
GCR6 - Well 206	4/29/2011	Arkoma	168	7.0
GCR6 - Well 207	4/29/2011	Arkoma	168	7.0
GCR6 - Well 208	4/27/2011	Arkoma	216	9.0
GCR6 - Well 209	4/27/2011	Arkoma	216	9.0
GCR6 - Well 210	5/2/2011	Arkoma	192	8.0
GCR6 - Well 211	5/3/2011	Arkoma	168	7.0



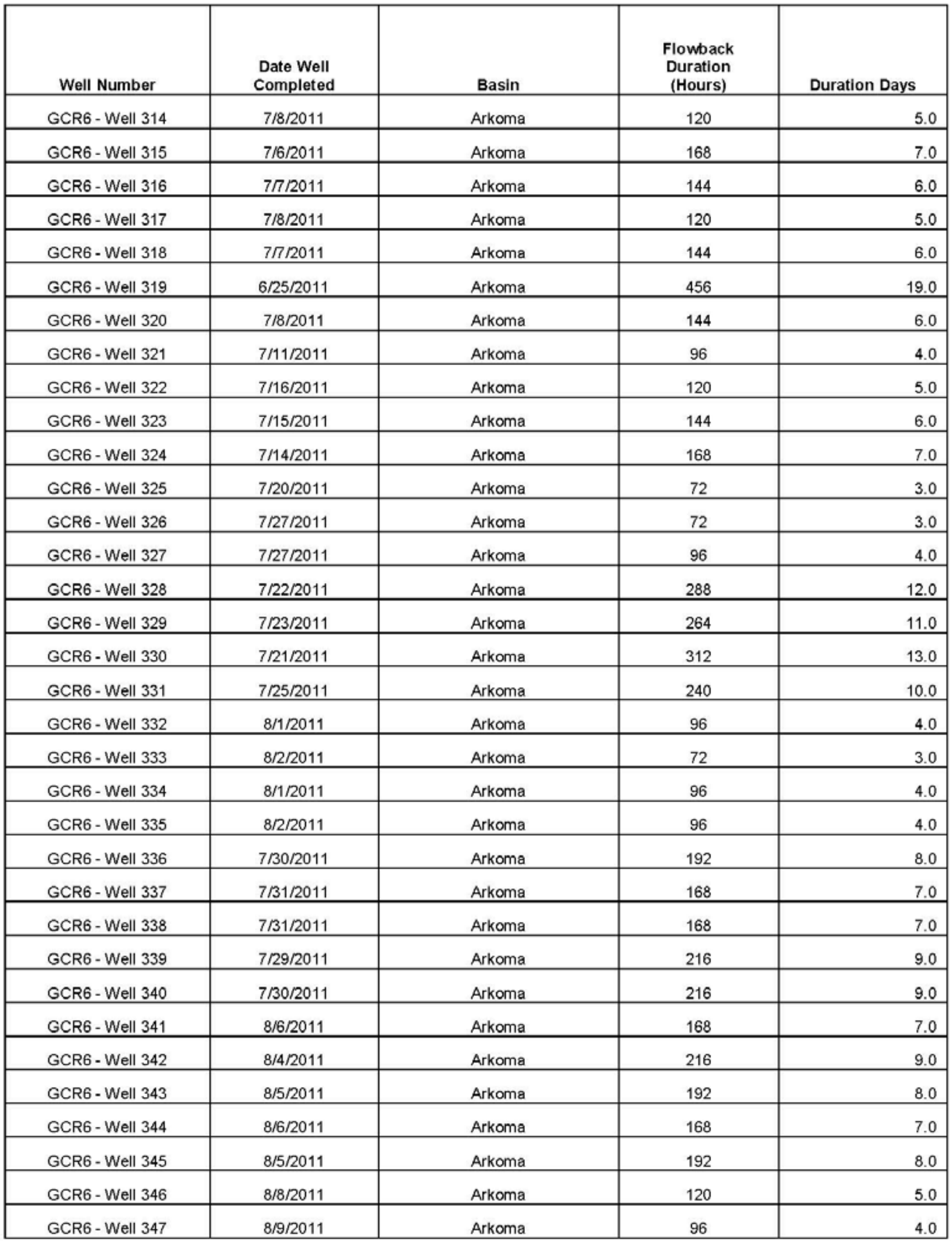
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 212	5/2/2011	Arkoma	192	8.0
GCR6 - Well 213	5/5/2011	Arkoma	168	7.0
GCR6 - Well 214	5/6/2011	Arkoma	144	6.0
GCR6 - Well 215	5/6/2011	Arkoma	144	6.0
GCR6 - Well 216	5/6/2011	Arkoma	144	6.0
GCR6 - Well 217	5/7/2011	Arkoma	144	6.0
GCR6 - Well 218	5/8/2011	Arkoma	120	5.0
GCR6 - Well 219	5/6/2011	Arkoma	168	7.0
GCR6 - Well 220	5/4/2011	Arkoma	216	9.0
GCR6 - Well 221	5/5/2011	Arkoma	192	8.0
GCR6 - Well 222	5/5/2011	Arkoma	192	8.0
GCR6 - Well 223	5/9/2011	Arkoma	144	6.0
GCR6 - Well 224	5/10/2011	Arkoma	120	5.0
GCR6 - Well 225	5/13/2011	Arkoma	144	6.0
GCR6 - Well 226	5/17/2011	Arkoma	72	3.0
GCR6 - Well 227	5/13/2011	Arkoma	168	7.0
GCR6 - Well 228	5/14/2011	Arkoma	144	6.0
GCR6 - Well 229	4/15/2011	Arkoma	840	35.0
GCR6 - Well 230	4/15/2011	Arkoma	840	35.0
GCR6 - Well 231	5/18/2011	Arkoma	72	3.0
GCR6 - Well 232	5/18/2011	Arkoma	72	3.0
GCR6 - Well 233	5/16/2011	Arkoma	120	5.0
GCR6 - Well 234	5/17/2011	Arkoma	96	4.0
GCR6 - Well 235	5/16/2011	Arkoma	168	7.0
GCR6 - Well 236	5/17/2011	Arkoma	144	6.0
GCR6 - Well 237	5/16/2011	Arkoma	168	7.0
GCR6 - Well 238	5/17/2011	Arkoma	168	7.0
GCR6 - Well 239	5/19/2011	Arkoma	144	6.0
GCR6 - Well 240	5/19/2011	Arkoma	144	6.0
GCR6 - Well 241	5/22/2011	Arkoma	120	5.0
GCR6 - Well 242	5/23/2011	Arkoma	96	4.0
GCR6 - Well 243	5/22/2011	Arkoma	120	5.0
GCR6 - Well 244	5/24/2011	Arkoma	72	3.0
GCR6 - Well 245	5/23/2011	Arkoma	96	4.0



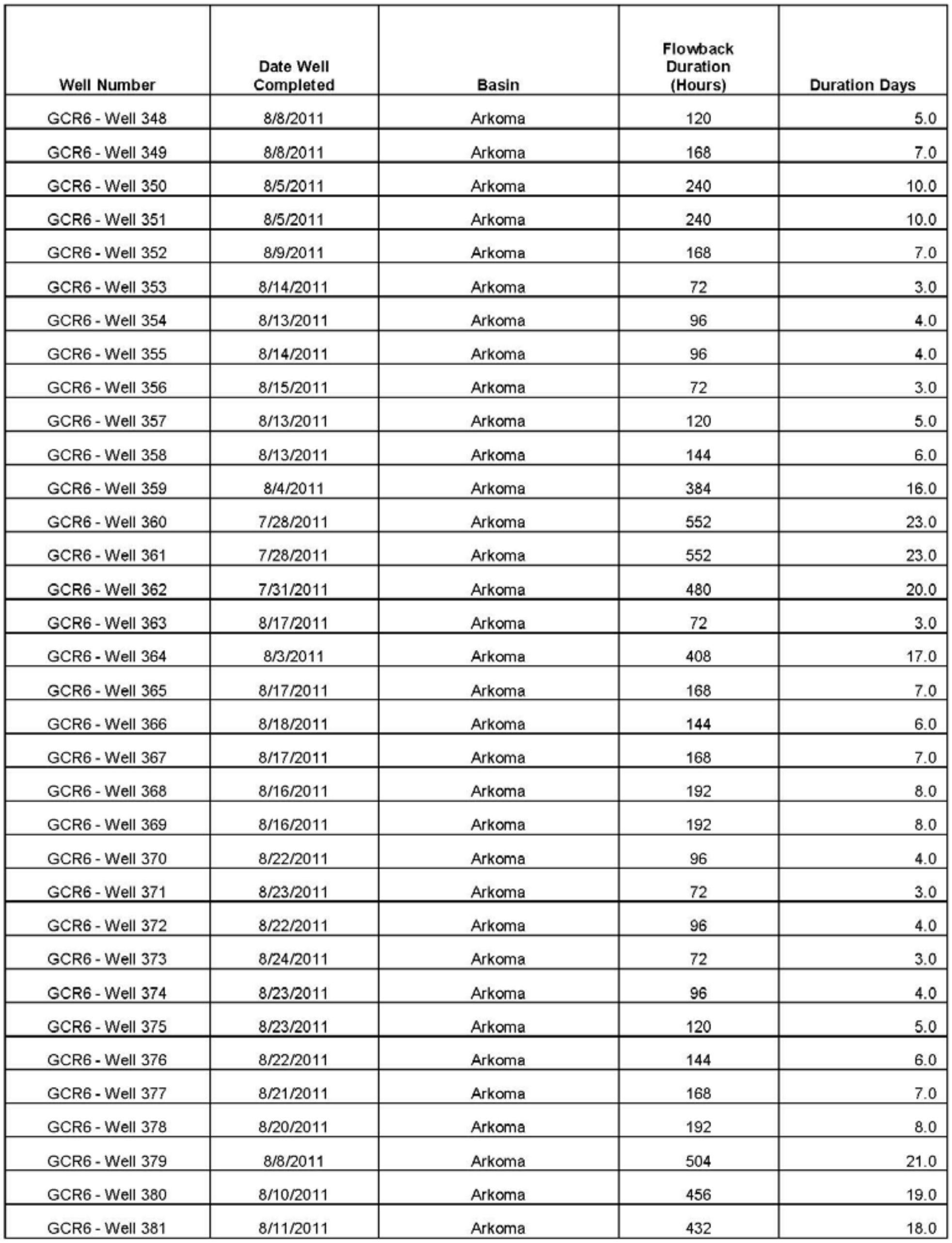
Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 246	5/24/2011	Arkoma	72	3.0
GCR6 - Well 247	5/2/2011	Arkoma	624	26.0
GCR6 - Well 248	5/9/2011	Arkoma	528	22.0
GCR6 - Well 249	5/25/2011	Arkoma	192	8.0
GCR6 - Well 250	5/26/2011	Arkoma	168	7.0
GCR6 - Well 251	5/25/2011	Arkoma	192	8.0
GCR6 - Well 252	5/25/2011	Arkoma	192	8.0
GCR6 - Well 253	5/26/2011	Arkoma	168	7.0
GCR6 - Well 254	5/25/2011	Arkoma	192	8.0
GCR6 - Well 255	5/27/2011	Arkoma	168	7.0
GCR6 - Well 256	5/27/2011	Arkoma	192	8.0
GCR6 - Well 257	5/28/2011	Arkoma	168	7.0
GCR6 - Well 258	5/27/2011	Arkoma	192	8.0
GCR6 - Well 259	5/28/2011	Arkoma	168	7.0
GCR6 - Well 260	6/1/2011	Arkoma	168	7.0
GCR6 - Well 261	5/31/2011	Arkoma	192	8.0
GCR6 - Well 262	6/2/2011	Arkoma	144	6.0
GCR6 - Well 263	6/1/2011	Arkoma	168	7.0
GCR6 - Well 264	5/31/2011	Arkoma	192	8.0
GCR6 - Well 265	6/3/2011	Arkoma	144	6.0
GCR6 - Well 266	6/2/2011	Arkoma	168	7.0
GCR6 - Well 267	6/2/2011	Arkoma	168	7.0
GCR6 - Well 268	6/1/2011	Arkoma	192	8.0
GCR6 - Well 269	6/3/2011	Arkoma	144	6.0
GCR6 - Well 270	6/3/2011	Arkoma	144	6.0
GCR6 - Well 271	6/7/2011	Arkoma	72	3.0
GCR6 - Well 272	6/6/2011	Arkoma	96	4.0
GCR6 - Well 273	6/6/2011	Arkoma	96	4.0
GCR6 - Well 274	6/6/2011	Arkoma	96	4.0
GCR6 - Well 275	6/6/2011	Arkoma	120	5.0
GCR6 - Well 276	6/7/2011	Arkoma	96	4.0
GCR6 - Well 277	1/26/2011	Arkoma	3336	139.0
GCR6 - Well 278	6/6/2011	Arkoma	192	8.0
GCR6 - Well 279	6/7/2011	Arkoma	168	7.0



Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 280	6/5/2011	Arkoma	240	10.0
GCR6 - Well 281	6/4/2011	Arkoma	264	11.0
GCR6 - Well 282	6/5/2011	Arkoma	240	10.0
GCR6 - Well 283	6/4/2011	Arkoma	264	11.0
GCR6 - Well 284	6/13/2011	Arkoma	72	3.0
GCR6 - Well 285	6/15/2011	Arkoma	168	7.0
GCR6 - Well 286	6/14/2011	Arkoma	192	8.0
GCR6 - Well 287	6/20/2011	Arkoma	72	3.0
GCR6 - Well 288	3/28/2011	Arkoma	2088	87.0
GCR6 - Well 289	6/16/2011	Arkoma	168	7.0
GCR6 - Well 290	6/17/2011	Arkoma	144	6.0
GCR6 - Well 291	6/15/2011	Arkoma	192	8.0
GCR6 - Well 292	6/16/2011	Arkoma	168	7.0
GCR6 - Well 293	6/20/2011	Arkoma	96	4.0
GCR6 - Well 294	6/24/2011	Arkoma	96	4.0
GCR6 - Well 295	6/25/2011	Arkoma	72	3.0
GCR6 - Well 296	6/27/2011	Arkoma	120	5.0
GCR6 - Well 297	6/27/2011	Arkoma	120	5.0
GCR6 - Well 298	6/28/2011	Arkoma	96	4.0
GCR6 - Well 299	6/24/2011	Arkoma	192	8.0
GCR6 - Well 300	6/23/2011	Arkoma	216	9.0
GCR6 - Well 301	6/28/2011	Arkoma	96	4.0
GCR6 - Well 302	6/22/2011	Arkoma	264	11.0
GCR6 - Well 303	6/19/2011	Arkoma	336	14.0
GCR6 - Well 304	6/14/2011	Arkoma	456	19.0
GCR6 - Well 305	7/1/2011	Arkoma	48	2.0
GCR6 - Well 306	6/27/2011	Arkoma	216	9.0
GCR6 - Well 307	6/28/2011	Arkoma	192	8.0
GCR6 - Well 308	6/27/2011	Arkoma	216	9.0
GCR6 - Well 309	6/28/2011	Arkoma	192	8.0
GCR6 - Well 310	7/6/2011	Arkoma	72	3.0
GCR6 - Well 311	7/6/2011	Arkoma	72	3.0
GCR6 - Well 312	7/7/2011	Arkoma	48	2.0
GCR6 - Well 313	7/6/2011	Arkoma	168	7.0



Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 314	7/8/2011	Arkoma	120	5.0
GCR6 - Well 315	7/6/2011	Arkoma	168	7.0
GCR6 - Well 316	7/7/2011	Arkoma	144	6.0
GCR6 - Well 317	7/8/2011	Arkoma	120	5.0
GCR6 - Well 318	7/7/2011	Arkoma	144	6.0
GCR6 - Well 319	6/25/2011	Arkoma	456	19.0
GCR6 - Well 320	7/8/2011	Arkoma	144	6.0
GCR6 - Well 321	7/11/2011	Arkoma	96	4.0
GCR6 - Well 322	7/16/2011	Arkoma	120	5.0
GCR6 - Well 323	7/15/2011	Arkoma	144	6.0
GCR6 - Well 324	7/14/2011	Arkoma	168	7.0
GCR6 - Well 325	7/20/2011	Arkoma	72	3.0
GCR6 - Well 326	7/27/2011	Arkoma	72	3.0
GCR6 - Well 327	7/27/2011	Arkoma	96	4.0
GCR6 - Well 328	7/22/2011	Arkoma	288	12.0
GCR6 - Well 329	7/23/2011	Arkoma	264	11.0
GCR6 - Well 330	7/21/2011	Arkoma	312	13.0
GCR6 - Well 331	7/25/2011	Arkoma	240	10.0
GCR6 - Well 332	8/1/2011	Arkoma	96	4.0
GCR6 - Well 333	8/2/2011	Arkoma	72	3.0
GCR6 - Well 334	8/1/2011	Arkoma	96	4.0
GCR6 - Well 335	8/2/2011	Arkoma	96	4.0
GCR6 - Well 336	7/30/2011	Arkoma	192	8.0
GCR6 - Well 337	7/31/2011	Arkoma	168	7.0
GCR6 - Well 338	7/31/2011	Arkoma	168	7.0
GCR6 - Well 339	7/29/2011	Arkoma	216	9.0
GCR6 - Well 340	7/30/2011	Arkoma	216	9.0
GCR6 - Well 341	8/6/2011	Arkoma	168	7.0
GCR6 - Well 342	8/4/2011	Arkoma	216	9.0
GCR6 - Well 343	8/5/2011	Arkoma	192	8.0
GCR6 - Well 344	8/6/2011	Arkoma	168	7.0
GCR6 - Well 345	8/5/2011	Arkoma	192	8.0
GCR6 - Well 346	8/8/2011	Arkoma	120	5.0
GCR6 - Well 347	8/9/2011	Arkoma	96	4.0



Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 348	8/8/2011	Arkoma	120	5.0
GCR6 - Well 349	8/8/2011	Arkoma	168	7.0
GCR6 - Well 350	8/5/2011	Arkoma	240	10.0
GCR6 - Well 351	8/5/2011	Arkoma	240	10.0
GCR6 - Well 352	8/9/2011	Arkoma	168	7.0
GCR6 - Well 353	8/14/2011	Arkoma	72	3.0
GCR6 - Well 354	8/13/2011	Arkoma	96	4.0
GCR6 - Well 355	8/14/2011	Arkoma	96	4.0
GCR6 - Well 356	8/15/2011	Arkoma	72	3.0
GCR6 - Well 357	8/13/2011	Arkoma	120	5.0
GCR6 - Well 358	8/13/2011	Arkoma	144	6.0
GCR6 - Well 359	8/4/2011	Arkoma	384	16.0
GCR6 - Well 360	7/28/2011	Arkoma	552	23.0
GCR6 - Well 361	7/28/2011	Arkoma	552	23.0
GCR6 - Well 362	7/31/2011	Arkoma	480	20.0
GCR6 - Well 363	8/17/2011	Arkoma	72	3.0
GCR6 - Well 364	8/3/2011	Arkoma	408	17.0
GCR6 - Well 365	8/17/2011	Arkoma	168	7.0
GCR6 - Well 366	8/18/2011	Arkoma	144	6.0
GCR6 - Well 367	8/17/2011	Arkoma	168	7.0
GCR6 - Well 368	8/16/2011	Arkoma	192	8.0
GCR6 - Well 369	8/16/2011	Arkoma	192	8.0
GCR6 - Well 370	8/22/2011	Arkoma	96	4.0
GCR6 - Well 371	8/23/2011	Arkoma	72	3.0
GCR6 - Well 372	8/22/2011	Arkoma	96	4.0
GCR6 - Well 373	8/24/2011	Arkoma	72	3.0
GCR6 - Well 374	8/23/2011	Arkoma	96	4.0
GCR6 - Well 375	8/23/2011	Arkoma	120	5.0
GCR6 - Well 376	8/22/2011	Arkoma	144	6.0
GCR6 - Well 377	8/21/2011	Arkoma	168	7.0
GCR6 - Well 378	8/20/2011	Arkoma	192	8.0
GCR6 - Well 379	8/8/2011	Arkoma	504	21.0
GCR6 - Well 380	8/10/2011	Arkoma	456	19.0
GCR6 - Well 381	8/11/2011	Arkoma	432	18.0

Well Number	Date Well Completed	Basin	Flowback Duration (Hours)	Duration Days
GCR6 - Well 382	8/25/2011	Arkoma	216	9.0
GCR6 - Well 383	8/25/2011	Arkoma	216	9.0
GCR6 - Well 384	8/25/2011	Arkoma	216	9.0
GCR6 - Well 385	8/26/2011	Arkoma	192	8.0
GCR6 - Well 386	9/1/2011	Arkoma	144	6.0
GCR6 - Well 387	8/31/2011	Arkoma	168	7.0
GCR6 - Well 388	9/1/2011	Arkoma	144	6.0
GCR6 - Well 389	8/31/2011	Arkoma	168	7.0
GCR6 - Well 390	8/29/2011	Arkoma	240	10.0
GCR6 - Well 391	8/30/2011	Arkoma	216	9.0
GCR6 - Well 392	8/30/2011	Arkoma	216	9.0
GCR6 - Well 393	8/30/2011	Arkoma	216	9.0
GCR6 - Well 394	8/29/2011	Arkoma	240	10.0
GCR6 - Well 395	8/29/2011	Arkoma	264	11.0
GCR6 - Well 396	1/2/2011	East Texas	386	16.1
GCR6 - Well 397	1/28/2011	East Texas	451	18.8
GCR6 - Well 398	2/24/2011	East Texas	402	16.8
GCR6 - Well 399	4/11/2011	East Texas		

Commenter: Karen Ritter, API

Comment: *A key revision to the natural gas inventory for 2010 is a change in terminology from conventional and unconventional gas wells to wells with and without hydraulic fracturing. Although API appreciates the revisions to the terminology to be more consistent with industry convention and reporting under Subpart W, this nomenclature change highlights inconsistencies with the well counts reported by EPA.*

There seems to be a disconnect between the number of wells drilled and the number of new well completions. EPA"s draft national inventory indicates 20,962 gas wells drilled for 2010, while only 4,296 wells were completed. Based on EPA"s inventory data, it appears that only 20% of the gas wells drilled are completed, which is far lower than the ratio of wells completed to wells drilled in practice. API notes the following additional inconsistencies in the well counts: For the Southwest Region almost twice as many wells were completed than drilled. For the Rocky Mountain Region, there is a significant decline in the number of producing non-associated gas wells, even with 3,800 wells drilled in that region. The number of wells completed for the North East and Midcontinent regions is much lower than the increase in non-associated gas producing wells from 2009 to 2010. These discrepancies should be explained.

API recognizes that correcting these issues will increase the count of gas well completions used in the inventory, and therefore increase the estimate of GHG emissions for Natural Gas Systems. With the numerous inconsistencies between the number of wells drilled, wells completed and well workovers, it is even more critical to re-evaluate the emission factor that EPA uses for gas well completions and workovers with hydraulic fracturing. API and ANGA are continuing to collect activity information to develop a more appropriate emission estimation method and resulting emission factors for gas well workovers and completions, and will share this information in the future.

Commenter: Karen Ritter, API

Comment: *API requests that EPA document the standard conditions used to convert emissions data from volumetric basis (scf) to mass basis (Mg). In spot checking the emission calculations presented in Table A-122, API calculates values slightly less than are reported in the table, using industry standard conditions of 60 ºF and 14.7 psia. It appears that EPA is applying a temperature slightly higher than 60 ºF and/or a pressure slightly below 14.7 psia.*

Commenter: Karen Ritter, API

Comment: *For Natural Gas Systems, EPA provides the total sector emission reductions in Tables A-127 and A-128, for Natural Gas STAR and regulatory driven reductions, respectively, while the unadjusted emission factors (i.e. emission factors that do not account for emission reductions) are reported in Tables A-122 through A-125. On page 3-51, lines 26 through 28, EPA indicates that they are planning to revise the emissions tables in Annex 3.4 to show voluntary reductions broken out for key emission sources. API supports this proposed change.*

Commenter: Karen Ritter, API

Comment: *On page 3-51, lines 4 through 6, EPA indicates that they are planning to improve the emission estimates for hydraulic fracturing. As commented previously, API believes the emission factor for gas well completions and workovers with hydraulic fracturing is significantly overestimated. API offers to work with EPA to develop more accurate emission factors for these sources.*

On page A-158, EPA documents a well workover rate of 10% based on an assumption from Advanced Resources International and production opinion cited in a life cycle analysis study1. However, in reviewing the referenced report, a workover rate of 10% is not mentioned. Workover rates are provided for a total of 87 wells located in Trinidad & Tobago, Nigeria, Egypt, and Algeria based on 2006 data. As noted previously, API believes this re-fracture rate is too high. More precise information will be available through the Mandatory GHG reporting program, with 2011 data reported to EPA in September 2012.

EPA has noted that they intend to revisit the estimates for gas well workover frequency (Page 3-51, lines 4-6). The 2010 GHG inventory does not incorporate the revised workover rate that EPA provided for discussion in July 2011 which would have revised the annual workover frequency from 10% to 0.3% based on information provided by one Gas STAR Partner. API is also gathering information to improve this workover rate.

Commenter: Karen Ritter, API

Comment: *For consistency with the GHG reporting rule and for better clarity, API requests that EPA refer to this emission source as gas wells with liquids unloading. The terminology well clean ups for low pressure wells is carried over from the original GRI/EPA study and does not adequately describe this emission source.*

On page 3-51, lines 1 through 2, EPA indicates that they intend to evaluate additional data on emission reductions, particularly for gas well cleanups. API supports improvements to the emission estimates for this important source.

API is currently gathering data to improve the emission factor for gas well liquids unloading, and API will share this information with EPA when it is available. In the meantime, as API commented for the 2009 inventory and the expert review period for the 2010 inventory, EPA should publish the equation and the average characteristics used for developing the liquids unloading emission estimates for each basin. EPA should identify all artificial lift practices and other methods for reducing emissions from this source, and EPA should provide separate factors for controlled and uncontrolled liquids unloading activities.

Commenter: Karen Ritter, API

Comment: *The 2009 inventory included for the first time emission factors for centrifugal compressors by seal type (wet and dry seals, respectively) for the natural gas processing and natural gas transmission sectors. The emission factors for centrifugal compressors increased from 2008 to 2009, regardless of seal type. The resultant emissions increase was most significant in the gas processing sector. The 2010 inventory applies the same emission factors used for 2009.*

On page A-158, EPA documents the approach used to estimate dry seal and wet seal centrifugal compressors. A Gas Star presentation2 is cited as the source for 2003 data from compressor vendors reporting that 90% of new compressors are equipped with dry seals. The inventory document states Given that 90% of new centrifugal compressors since 2003 are equipped with dry seals, and that there were 0 dry seal compressors in 1992; EPA interpolated a straight-line estimate of the percentage of new compressors that were equipped with dry seals, based on pipeline mileage. More precise information will be available through the Mandatory GHG reporting program, with 2011 data reported to EPA in September 2012.

API has commented previously that the basis of the EPA wet seal emission factors is not clear and is inconsistent with Subpart W of the EPA"s GHGRP. API has also requested that EPA explain the derivation of the wet and dry seal emission factors and clearly state the reference of the emission factors for each segment. API requests that EPA address these comments.

Commenter: Karen Ritter, API

Comment: *On page A-157, EPA notes, The same emission factors are used for each year throughout this period (1990 through 2010) after adjusting for changes in methane content. If this is the case, one would expect a consistent increase or decrease in emission factors within a given NEMS region. However, exceptions are noted below for the well-based fugitive emission factors associated with hydraulically fractured gas wells (not to be confused with the venting emissions from workovers or completions on wells with hydraulic fracturing):*

- *Emissions in the North East and West Coast regions were previously shown as NE, or not estimated because there was no corresponding activity for that region. For 2010, these two sources apply the same emission factor as non-associated gas wells, though there is still no corresponding well activity data. There are some significant changes to this emission factor for other regions. For example, the emission factor for gas wells with hydraulic fracturing in the Midcontinent region nearly doubled from 2009, and the emission factor for the Rocky Mountain region increased from 6.97 scfd/well in 2009 to 40.03 scfd/well in 2010. The emission factor for non-associated gas wells in the Gulf Coast region decreased from 40.97 scfd/well in 2009 to 7.98 scfd/well in 2010. These changes are not explained.*
- *For the Midcontinent and Rocky Mountain regions, the emission factors decreased slightly from the values used in 2009, with the exception of the emission factors applied to gas well completions and workovers with hydraulic fracturing which increased. These changes are not explained and appear to conflict with a statement made on page 3-50, lines 25-27: EPA has held the 2010 estimate for emissions from hydraulically fractured gas wells constant at 2009 levels (i.e., maintained the same activity data and voluntary reductions for hydraulically fractured gas well completions and existing hydraulically fractured gas wells).*

Commenter: Karen Ritter, API

Comment: *EPA provides the CO2 content for different well types in Table A-133, but does not report the different CH4 contents used for each NEMS region. For transparency, API requests documentation of the CH4 contents used for each NEMS region.*

Commenter: Karen Ritter, API

Comment: *A footnote to Table A-133 indicates that the EPA inventory defines unconventional wells as those that are hydraulically fractured. As noted previously, API appreciates the revisions to the terminology associated with gas wells with and without hydraulic fracturing. However, API requests that the terminology be used consistently throughout the documentation for Natural Gas Systems in Annex 3.4. Specifically, the term unconventional is used in Step 4 on page A-159, Conventional Gas Wells is used for the North East workover emission source on page A-160, and the terms conventional and non-conventional are used in Table A-133.*

Commenter: Karen Ritter, API

Comment: *Although referenced in the first paragraph of Section 3.6 for Natural Gas Systems, the new table, Table 3-38 (starting on page 3-47), is not explained. It appears to present unadjusted total CO2e 7*

emissions for each sector of the Natural Gas Systems (i.e. before any emission reductions are accounted for) and the reductions reported in Tables A-127 and A-128. Then, Table 3-37 takes the Potential Emissions, and subtracts out the emission reductions. API suggests that EPA include an explanatory note for this table and revise the title of this table (potential emissions implies emission at their maximum theoretical capacity). It would also be useful for EPA to add total calculated emissions to Tables A-122 through A-125 to aid in comparing the results presented in the Annex to the discussion in Section 3.6 of the inventory report.

Commenter: Karen Ritter, API

Comment: *The number of oil well completions in Table A-138 and Table A-143 increased significantly from 11,804 in the 2009 inventory to 18,456 in the 2010 draft inventory. This large increase is not discussed. In addition, the number of oil wells drilled (20,794) and the number of oil well completions (18,456), both reported in Table A-138, are larger than the number of crude oil development and exploratory wells reported by EIA for 2010 (16,5793).*

Commenter: Karen Ritter, API

Comment: *As stated in comments during the Expert Review period, API appreciates the correction to the emissions from asphalt blowing. As noted in API"s comments on the 2009 national inventory and discussed during the webcast, the previous national inventory was applying an emission factor based on the volume of asphalt blown to the total amount of asphalt produced. This inconsistency in units was greatly overestimating emissions from asphalt blowing. The revisions incorporated in the 2010 inventory correct this error.*

Commenter: Karen Ritter, API

Comment: *API had noted in comments during the Expert Review period that there are a number of emission sources associated with the refinery sector that are included under the Industrial category of Fossil Fuel Combustion Emissions, consistent with the underlying energy consumption data from EIA and IPCC"s inventory methodologies. These include, in addition to combustion units, CO2 emissions from hydrogen production, catalytic cracking units, fluid coking units, catalytic reforming units and sulfur recovery units. There is some ambiguity – and a developing inconsistency – as to where CO2 emissions from flares, hydrogen production, and* *coke calcining units are reported, due to differences between the IPCC methods and source categorization as compared to EPA"s mandatory GHG Reporting Program (GHGRP).*

EPA indicates in the Planned Improvements discussion (page 3-55, starting on line 37) that data collected through 40 CFR Part 98 (GHGRP) will be used as a source for potential improvements to the national inventory. Further, EPA stated that In particular, EPA will investigate whether certain emissions sources currently accounted for in the Energy sector should be separately accounted for in the petroleum systems inventory (e.g., CO2 process emissions from hydrogen production). API supports the continued improvement of the national inventory, and urges EPA to prevent inadvertent double counting of emissions due to the different methodologies and source classifications used in the „top down" national inventory versus the „bottom up" facility-by-facility reporting required by the GHGRP. API also recommends that EPA provide transparent justification along with a formal technical review for anticipated changes to the national inventory methodology and process.

Commenter: Karen Ritter, API

Comment: *API had previously requested that EPA provide additional information in the Annex that indicates the source of each activity value and the method used to develop the activity value. Under the Planned Improvements (page 3-55, starting at line 42), EPA indicates that they are considering including a table matching each emission factor and activity factor with its source or calculation methodology. API supports this added transparency.*

Commenter: Karen Ritter, API

Comment: *Page A-157, 4th paragraph, line 5: the parenthetical … previously referred to as unconventional) , has an extra space before the comma.*

Commenter: Karen Ritter, API

Comment: *Page A-157, 5th paragraph, line 3: need to add a period and space between content and To*

Commenter: Karen Ritter, API

Comment: *Page A-158, 2nd paragraph, line 1: need to add a space between region and by.*

Commenter: Karen Ritter, API

Comment: *Page A-158, The first line of paragraphs 3 and 5 are not indented.*

Commenter: Karen Ritter, API

Comment: *Page 3-15, line 43: A comma is missing between production sector and uncombusted.*

Commenter: Karen Ritter, API

Comment: *There is an inconsistency in the wording between the last sentence of the first paragraph on p. A-157 (Many emission factors determined by EPA/GRI (1996) were assumed to be representative of emissions from each source type over the period 1990 through 2010.) and the first sentence three paragraphs later (Each emission factor in the U.S. Inventory was assumed to be representative of emissions from each source type over the period 1990 through 2010) – one says many and one says each.*

Commenter: Karen Ritter, API

Comment: *There is a period missing at the end of the first paragraph on p. A-159, after Table A-128.*

Commenter: Karen Ritter, API

Comment: *The number of platforms shown in Table A-126 does not match the number of platforms shown in Table A-122. It appears the values shown in Table A-126 may be a sum of the number of gas platforms, as shown in Annex 3.4, and the number of oil platforms, as shown in Annex 3.5. Although, even using this summation, the number of Gulf of Mexico and Pacific OCS Offshore Platforms does not match (a calculated 3,420 platforms vs. the value shown in Table A-126 of 3,432 platforms). Also, if the numbers shown in Table A-126 are indeed combined oil and gas production platforms, a comment should be provided indicating this.*

Commenter: Karen Ritter, API

Comment: *A footnote should be added to Table A-129 to explain what the + symbol means.*

Commenter: Karen Ritter, API

Comment: *The value of 1.410.09 in Table A-132 should be represented as 1,410.09*

Commenter: Karen Ritter, API

Comment: *The reference to Table A- 5 on row 30 of p. A-176 needs to be updated.*

Commenter: Karen Ritter, API

Comment: *The reference to Table A-140 on row 8 of p. A-177 should instead reference Table A-142.*

Commenter: Karen Ritter, API

Comment: *Row 13, p. 3-47 references 258,000 miles in 1990, but according to Table A-126, the value should be 944,157 miles.*

Commenter: Karen Ritter, API

Comment: *The totals shown for Table 3-40 do not match the values shown in Table 3-2. It appears there is a summation error for Table 3-40.*

Commenter: Karen Ritter, API

Comment: *A comment we have provided previously, when a table is split onto multiple pages, it would be useful to add a table title to each subsequent page, for transparency.*

Commenter: El Paso Corporation

Comment: *EPA Methane Emissions Estimation Methods Are Not Transparent And Need Significant Improvement*

EPA national inventories employ a 6 step process to estimate net emissions from each segment. The methodology relies on computing uncontrolled emissions first and then backing out reductions that may have been achieved via voluntary and/or state/federal requirements. The uncontrolled emissions are the product of activity data and an emission factor for each source category.

EPA must provide greater clarity to the amount of reductions at a unit or component level achieved via voluntary and mandatory reduction programs. In other words, Tables A-127 and 128 must be more transparent, detailed and possibly resemble the format employed in A-122 to A-126 in Annex 3 of the DRAFT Inventory. It is impossible to assess whether EPA has accurately depicted the current state of reduction technologies employed by the industry based on the information provided in Tables A-127 and A-128.

Commenter: El Paso Corporation

Comment: *EPA and EIA Emission Estimates and Emission Methodologies Must Be Reconciled*

On March 31, 2011, the U.S. Energy Information Administration (EIA) published its 18th annual report on 2009 annual emissions of GHGs in the United States8. While EIA employs a different global warming potential (GWP) for methane, we believe that EIA has much more robust activity data estimates to estimate methane emissions from the production, processing and T&S sectors of the US natural gas system than the EPA. Table 2-1 compares the EIA estimates for 2009 and the EPA estimates, including the revised 2009 methane estimates in this DRAFT inventory and the initial 2009 estimates finalized on April 15, 2011. After adjusting the EIA methane estimates to a GWP of 21, the EPA estimates are higher than the EIA estimates by 66.8 to 67.5 million metric ton of CO2e. While EIA has stopped publication of the annual GHG reports, but we urge the EPA to coordinate and reconcile emissions with the EIA, especially for the natural gas sector and use expertise residing at the EIA and Department of Energy (DOE) to better characterize and analyze emissions data from the industry.

Commenter: El Paso Corporation

Comment: *EPA Emission Factors Should Be Developed After Accounting Of Emission Controls And Current Infrastructure To Avoid Mischaracterization Of The True Emissions Profile Of the Natural Gas Industry*

EPA first computes the uncontrolled emissions and then backs out the voluntary and mandatory reductions through a very opaque process. EPA should employ all available data, including the data that will be submitted by companies as part of compliance with Subpart W reporting rules, to develop appropriate emission factors. Some of the revisions in estimation methodologies instituted by the EPA in 2009 were in response to the fact that once Natural Gas STAR Partner reported reductions are subtracted, it suggested that emissions from these emission sources are negative. While we welcome improvements in emissions estimates, it is unclear why EPA ignores reduction data when both the uncontrolled and controlled emissions are available. An example of such a situation is the EPA's derivation of an emission factor for well completions and workovers. The EPA analysis takes the simple average of four sets9 of completion flowbacks for the unconventional well completion emission factor: 9,175 Mcf/completion. As noted in El Paso's comments on the DRAFT inventory submitted on March 23, 2011, the majority of data for the above EPA factors came from Williams10 and completion factor was rounded up by the EPA to 20,000 Mcf of natural gas per well.

As noted above, EPA first computes the uncontrolled emissions and then backs out the voluntary and mandatory reductions through a very opaque process. EPA should employ all available data, including the data that will be submitted by companies as part of compliance with Subpart W reporting rules, to develop appropriate emission factors. Some of the revisions in estimation methodologies instituted by the EPA in 2009 were in response to the fact that once Natural Gas STAR Partner reported reductions are subtracted, it suggested that emissions from these emission sources are negative. While we welcome improvements in emissions estimates, it is unclear why EPA ignores reduction data when both the uncontrolled and controlled emissions are available. An example of such a situation is the EPA's derivation of an emission factor for well completions and workovers. The EPA analysis takes the simple average of four sets9 of completion flowbacks for the unconventional well completion emission factor: 9,175 Mcf/completion. As noted in El Paso's comments on the DRAFT inventory submitted on March 23, 2011, the majority of data for the above EPA factors came from Williams10 and completion factor was rounded up by the EPA to 20,000 Mcf of natural gas per well. The relevant portion of the presentation is reproduced in Figure 1.

While the Williams data contained both the actual volumes of "completion gas generated" and "flowback gas recovered", the EPA chose to use the "completion gas generated". Had EPA used the flowback recovery data by Williams provided in the same data set, and conservatively assuming there was zero flaring- i.e. all non recovered gas was vented and nothing was flared, one would end up with a weighted emission factor of 2,633/completion employing a 2002-2006 vintage dataset. Table 2-2 shows a significantly lower emission factor when the actual completion gas released to the atmosphere is considered, rather than trying to estimate the emissions based on the amount of gas recovered from the green completion. Even the results shown in Table 2-2 are overestimating emissions, as Williams notes that some of the non-

recovered completion gas is flared rather than vented. A more significant difference results from excluding the 2002 data, which may demonstrate that Williams improved on the amount of gas recovered from a completion in recent years (from 61% in 2002 to 90% or more in recent years). In fact, a recent analysis by ANGA concludes that the "EPA's 9,175 Mscf/completion event for unconventional fractured wells is potentially overestimating emissions by 1,200%."

The above example clearly points out the weakness in EPA's computing methodology where the EPA first computes uncontrolled emissions and then backs out reductions even when data on emissions post application of controls is available from the same source. It is surprising that EPA reverts to this methodology for sources like workovers and well clean-ups while for condensate tanks, separate emissions factors to account for both controlled and uncontrolled tanks are used.

EPA seems to be reluctant to analyze trends in industry to employ more "reduced emission completions" or RECs as shale plays and gas infrastructure within these plays become more mature. As noted above, this phenomenon is reinforced in the Williams data (employed by EPA to develop the workover and completions emission factors) as the latest year (2006) of data indicates over 90% capture of emissions which is also consistent with a recent ANGA study. The ANGA study concluded from its dataset that 93% of 2011 well completions had "green completions" and of the remaining "7% that were non-green completed, 54% were flared rather than directly vented to atmosphere. This indicates that only approximately 3% of the well completions in the dataset were uncontrolled." In other words, EPA's emission factor for flowbacks is outdated and grossly over-estimates the emissions from well completion.

It is no surprise that many of the non-industry stakeholders perceive the uncontrolled emissions from the EPA inventories as a reflection of "normal operations" by the industry. EPA must characterize the emission factors for both controlled and uncontrolled sources. EPA has already done the same for emissions from condensate storage tanks associated with the natural gas industry. Vapor recovery units (VRUs) are commonly utilized to control emissions from condensate tanks in the natural gas sector. EPA assumes 80% emission reduction to account for VRU usage. Typical VRU control efficiencies are much higher but nevertheless, this approach results in improved estimates of condensate tank emissions. EPA should carry out the same methodology for other major emission source categories such as liquids unloading, well completions, well workovers, pneumatic devices, compressor seals etc. Control technologies such as plunger-lifts, RECs, low bleed pneumatics and dry seals that are widely applied must be incorporated into the emission factors. In summary, El Paso urges the EPA to develop emission factors from all relevant and recent data sources (such as data from Subpart W reporting) to characterize emissions from major source categories post emissions controls. The EPA should collect activity data that includes the number or percentage of sources employing emission controls and their types. The current methodology of first computing uncontrolled emissions and *then backing out natural gas reductions (a process that is very opaque) has already resulted in significant mischaracterization of the industry's actual emissions.*

Well Clean Up Is The Largest Source Of Uncontrolled Emissions But Revised Methodology Employs Outdated Data And There Is No Transparency On Reductions From Emission Reduction Technologies

While there has been significant focus by various entities on methane emissions, especially related to "flowbacks" from unconventional well completions and workovers, the largest uncontrolled emission category per the EPA inventory is well clean up (liquids unloading) - an event associated with conventional low-pressure wells. Per the EPA well completions contribute approximately 4% of the total emissions from the combined production, processing and T&S sectors; well clean up contributes approximately 37% of the combined emissions prior to emission controls. Prior to the 2009 revisions, the EPA employed an emission factor of 49,570 standard cubic feet of methane per year from well clean ups and assumed three scaling factors at three points over the time a well is blown down. In the revised methodology, EPA uses data from well sites from 1992 to conclude that 41.3 % of conventional wells require liquid unloading and assumes this as a constant from 1992 to present - despite the trend of shale gas production accounting now for a larger share of the total gas production which should imply a decrease in the liquids unloading at low pressure convention wells. In addition, the EPA uses the 1992 data survey from 25 wells to conclude that there are "38.73 blowdowns per year per well" that require unloading – a precision to the second decimal point of the number of annual blowdowns per year per well! As noted in our 2011 comments, the most significant issue with the approach applied to quantify low pressure well clean up emissions, and also a universal issue with the EPA's national inventories, is that the methodologies are not transparent when first uncontrolled emissions are computed and then the reductions reported via voluntary or mandatory mechanisms are backed out. We recommend that the EPA provide separate factors for controlled and uncontrolled emissions, and compute actual emissions using data from Subpart W reports.

Comments and Recommendations – Transmission & Storage Sector a. Background - Dry & Wet Seal Centrifugal Compressors

In our 2009 comments, El Paso provided details related to estimates of emissions from centrifugal compressors. In our comments, we concluded that EPA incorrectly averaged12 the data from a 48 sample data set presented in a World Gas Conference paper (WGC 2009). If an emission factor calculated by using the correct average of the WGC data had been used in the draft inventory, the emissions due to compressor wet seal would be reduced to 58% of the current estimate for processing, 60% of the current estimate for transmission, and 66% of the current estimate for storage. This would have reduced the total inventory for the processing sector by approximately 10.4%, and the total inventory for the transmission/storage sector by approximately 4.2%.

To arrive at the dry seal emission factor, the EPA assumed that the midpoint (3 scfm) of the reported Lessons Learned13 range of up to 6 scfm adequately characterized dry seals. Since there are typically 2 dry seals per compressor, the total per-compressor emissions rate from dry seals is 6 scfm.

To arrive with a number of compressors using dry seals, EPA's main source was a presentation from 2003 on centrifugal compressors in the natural gas industry14 which showed that 90% of new compressors sold were equipped with dry seals. EPA assumed that all centrifugal compressors installed prior to 1992 were equipped with wet seals. Assuming that 90% of new centrifugal compressors since 2003 were equipped with dry seals, and that there were none dry seal compressors in 1992, the EPA interpolated a straight-line estimate of the percentage of new compressors that were equipped with dry seals. That is, the percentage of new compressors equipped with dry seals increased linearly between 0% in 1992 and 90% in 2003.

El Paso Actual Measurements

This section provides El Paso's measured emission factors and activity data for major "unit" level emission sources at its pipeline facilities. This data was collected as part of compliance efforts with Subpart W regulations.

El Paso's Pipeline Group is the nation's leading interstate natural gas pipeline franchise as measured not only by mileage, but more importantly, by access to key supply regions and major consuming markets as well as by unparalleled connectivity to those markets. We transport 17 billion cubic feet per day or 26 percent of the gas delivered to U.S. consumers each day through our 42,000 mile interstate natural gas pipeline system. Our pipelines have the capacity to transport up to 28 billion cubic feet per day, 13 percent of the total U.S. natural gas pipeline capacity.

Our pipelines reach deep into the traditional Gulf Coast supply areas, the prolific Rockies supply basins, and the shale plays that will play a significant role in meeting the nation's long-term natural gas supply. We serve the major consuming markets of the Northeast, Southeast, Rockies, and Southwest, as well as Mexico. Our pipelines are built deep into our markets, making us a critical part of the infrastructure of local distribution companies, storage operations, and industrial and power generation facilities. As of December 31, 2012, we have placed into service 1,800 miles of new pipelines as part of our $8 billion natural gas pipeline expansion program in the recent years.

Due to the above reasons, our pipeline network is a good reflection of the natural gas pipeline industry in the U.S. Hence, the results of our methane measurement program that surveyed over 200 facilities, provides a much more significant insight to the emissions profile of the industry *than outdated emissions estimation from the early 1990s derived from a significantly lower sample size and/or linear interpolation of data to arrive at best guess of the emissions.*

El Paso's Pipelines Emissions Measurement & Estimation Program.

El Paso has been participating in the EPA Natural Gas Star program since 1993 and has been recognized as the "Partner of the Year" multiple times. Through the Natural Gas Star program and internal voluntary monitoring initiatives, El Paso gained superior technical knowledge on the capabilities and limitations related to fugitive emission monitoring and reductions in the natural gas sector. Since 1993, the El Paso Pipeline Group achieved GHG emission reductions of over 63 billion cubic feet of natural gas, or approximately 30 million tons of CO2e. El Paso has implemented fugitive and vented methane leak measurement and research programs dating back to the 1990s. We have experience in practical applications of various tools such as the Infra-red camera, Hi-Flow Sampler etc.

El Paso has been a member of the California Climate Action Registry (CCAR) since 2006 and has been reporting its GHG emissions since 2007. In August 2008, El Paso became the first company to file an emissions inventory covering all applicable GHGs, including methane, N2O and CO2 for its US operations. In addition, on December 31, 2007, El Paso reported its 2006 GHG emission estimates under DOE 1605(b) requirements. The CCAR inventories followed CCAR protocols and INGAA guidelines for estimation of emissions. The INGAA guidelines predominantly use the EPA/GRI data set from the 1990s. For El Paso's CCAR inventories, emissions were based on historical factors and actual activity data.

El Paso has developed a comprehensive monitoring and reporting program to ensure compliance with 40CFR Part 98 Subpart W (Subpart W) regulations. As part of this program, El Paso surveyed 193 compressor stations, 10 storage stations, 1 LNG plant and 7 processing plants. El Paso followed EPA survey and measurement protocols outlined in Subpart W. The data was then analyzed for each unit and component level emission source type. Table 3-1 provides a summary of the preliminary16 emissions data from El Paso's data collection efforts a (averaged at the 95% confidence interval) versus the EPA emissions data for the same source.

As illustrated in Table 3-1, El Paso factors are significantly lower than the EPA factors and have been developed from a sample size that is in general superior in terms of quantity and measurement techniques. Table 3-2 compares El Paso component level emission rates for the source category - a natural gas transmission facility operating reciprocating compressor engines. The sum of the individual component leakers provides the unit level emissions estimates as noted in Table 3-1.

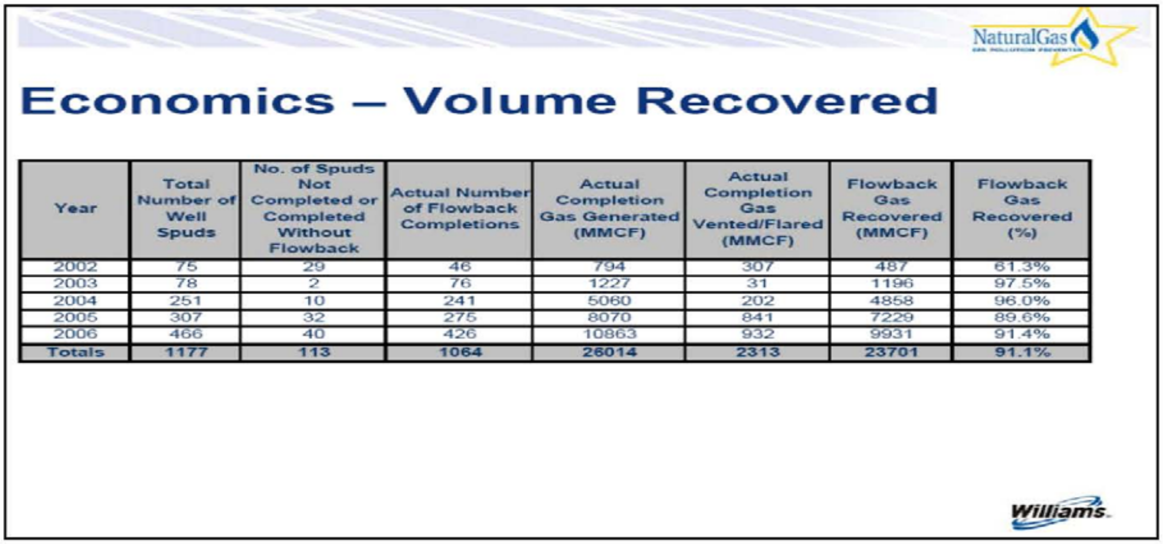
For this emission source category, the EPA source of the data and associated factor that is employed in the DRAFT inventory is the EPA/GRI study17. The sum total of these components equates to with the 5,550 MSCF/YR or 15,205 scfd leak rate that the EPA uses in Table A-124, *Annex 3 of the DRAFT Inventory to compute emissions from natural gas transmission facility operating reciprocating compressor engines.*

To ensure a correct comparison with the El Paso data, since the EPA Subpart W protocol does not include direct measurements and related calculations of leak rates from pressure relief valve and other miscellaneous components (but which were measured as part of the EPA/GRI study), those two leak rates are backed out from the EPA/GRI factor for comparison purposes. As such, an "adjusted" unit level EPA Leak rate excluding these two sources is 4,998 MSCF/YR or 13,693.2 scfd per compressor unit instead of 15,205 scfd. Whereas, the average El Paso unit level factor at the 95% confidence interval is 1,427 ±265MSCF/YR or 3,909.6±726 scfd.

Figure 3 is a histogram that depicts the El Paso the "unit level" emission rates from the above source category using data measured and calculated at 811 units (reciprocating compressor engines) using the EPA Subpart W protocol. The calculated unit level leak rate distribution clearly shows that El Paso compressor fugitives for this source category are significantly lower than EPA's estimates and there are only a handful of compressor fugitive emission rates (from a unit population size of 811) that exceeded the EPA factor.

Similarly, Figures 4, 5 and 6 are histograms of El Paso's calculated unit values versus EPA's unit level factors for compressor station fugitives (storage), centrifugal compressor station (wet seal) and centrifugal compressor station (dry seal). As noted above (with reciprocating compressor station fugitives), the summary data is presented in Table 3-1. In all cases, the measured value from El Paso results in significantly lower emissions than the factors employed by the EPA. It should also be noted that the El Paso sample size is statistically much more significant than the EPA sample size and unlike some EPA factors is not a linear interpolated or assumed value.

Figure 1 – Williams Flowback Data



Economics – Volume Recovered

Year	Total Number of Well Spuds	No. of Spuds Not Completed or Completed Without Flowback	Actual Number of Flowback Completions	Actual Completion Gas Generated (MMCF)	Actual Completion Gas Vented/Flared (MMCF)	Flowback Gas Recovered (MMCF)	Flowback Gas Recovered (%)
2002	75	29	46	794	307	487	61.3%
2003	78	2	76	1227	31	1196	97.5%
2004	251	10	241	5060	202	4858	96.0%
2005	307	32	275	8070	841	7229	89.6%
2006	466	40	426	10863	932	9931	91.4%
Totals	**1177**	**113**	**1064**	**26014**	**2313**	**23701**	**91.1%**

Table 2-2 – Analysis of Williams' Flowback Estimates

	Actual Number of Reported Flowback Completion	Actual Completion Gas or Natural Gas Flowrate Prior to Recovery or Flaring		Rounded Average Employed by EPA for Emission Factor Development	Reported Vented or Flared Emissions		Rounded Average Computed for Actual Vented or Flared Emissions
Source, Year		**MMCF**	**MCF/Completion**	**MCF/ Completion**	**MMCF**	**MCF/Completion**	**MCF/Completion**
Williams, 2002	46	794	17,261	**20,000**	307	6,674	**2,633**
Williams, 2003	76	1,227	16,145		31	408	
Williams, 2004	241	5,060	20,996		202	838	
Williams, 2005	275	8,070	29,345		841	3,058	
Williams, 2006	426	10,863	25,500		932	2,188	

🟩 Reported or computed directly from Williams Data
🟥 EPA Analysis
🟦 El Paso Analysis

Figure 2 – El Paso Pipeline Network

Table 3-1: Comparison of EPA Unit Level Emission Factors versus El Paso Factors

Emission Rates (standard cubic feet per day (scfd) per compressor unit)			Unit Population Size and Sample Size of Direct Measurements	
Source Category	**EPA**	**El Paso (average @95% CI)**	**EPA**	**El Paso**
Transmission Station Reciprocating Compressor Station Fugitives	15,205	1,427± 266	?	811 Units Calculated using EPA Subpart W protocol based on 350 Blowdown valve , 438 Rod Packing, and 336 Unit Isolation Valve Unit Level Direct Measurements
Transmission Centrifugal (Wet Seal) Compressor Fugitive	50,222	626± 314	48	138 Units Calculated using EPA Subpart W protocol based on 38 Blowdown valve , 11 Wet Seal, and 155 Unit Isolation Valve Unit Level Direct Measurements
Transmission Station Centrifugal (Dry Seal) Compressor Fugitive	32,208	401± 89	Assumed 3 scfm and converted to annual rates based on 30% operating factor	116 Units Calculated using EPA Subpart W protocol based on 38 Blowdown valve , 35 Dry Seal, and 155 Unit Isolation Valve Unit Level Direct Measurements
Storage Station Reciprocating Compressor Station Fugitive	21,116	1558± 358		54 Units Calculated using EPA Subpart W protocol based on 350 Blowdown valve , 438 Rod Packing, and 336 Unit Isolation Valve Unit Level Direct Measurements

Table 3-2: Comparison of 2011 Unit Average and Component Level Emission Factors – EPA and El Paso Pipelines

	Transportation Station Reciprocating Compressor Station Component Emission Factor	
Component Name	**EPA[a]**	**El Paso (@95% Confidence Interval)**
Compressor Blowdown Open-Ended Line (Combination of Idle-Pressured Blowdown Valve and Idle-Unpressurized Unit Isolation Valve Sources)	3,683 MSCF/YR = 10,090 scfd	720±255MSCF/YR = 1,972.6±698scfd
Pressure Relief valve	372 MSCF/YR = 1,019scfd	Not Measured as Part of Subpart W
Miscellaneous	180 MSCF/YR = 493 scfd	Not Measured as Part of Subpart W
Compressor Seal	1,315 MSCF/YR = 3602 scfd	707±87MSCF/YR = 1,938±238 scfd
EPA/GRI Total (Factor used in the DRAFT Inventory)	5,550 MSCF/YR = 15,205 scfd	
Adjusted EPA/GRI (Total – PRV – Misc.)	**4998 MSCF/YR = 13,693 scfd**	**1,427 ±266 MSCF/YR = 3,910±728 scfd**

Figure 3: Histogram of El Paso Pipeline Group (EPPG) 2011 Transmission Station Reciprocating Compressor Fugitive Emissions in MSCF/YR

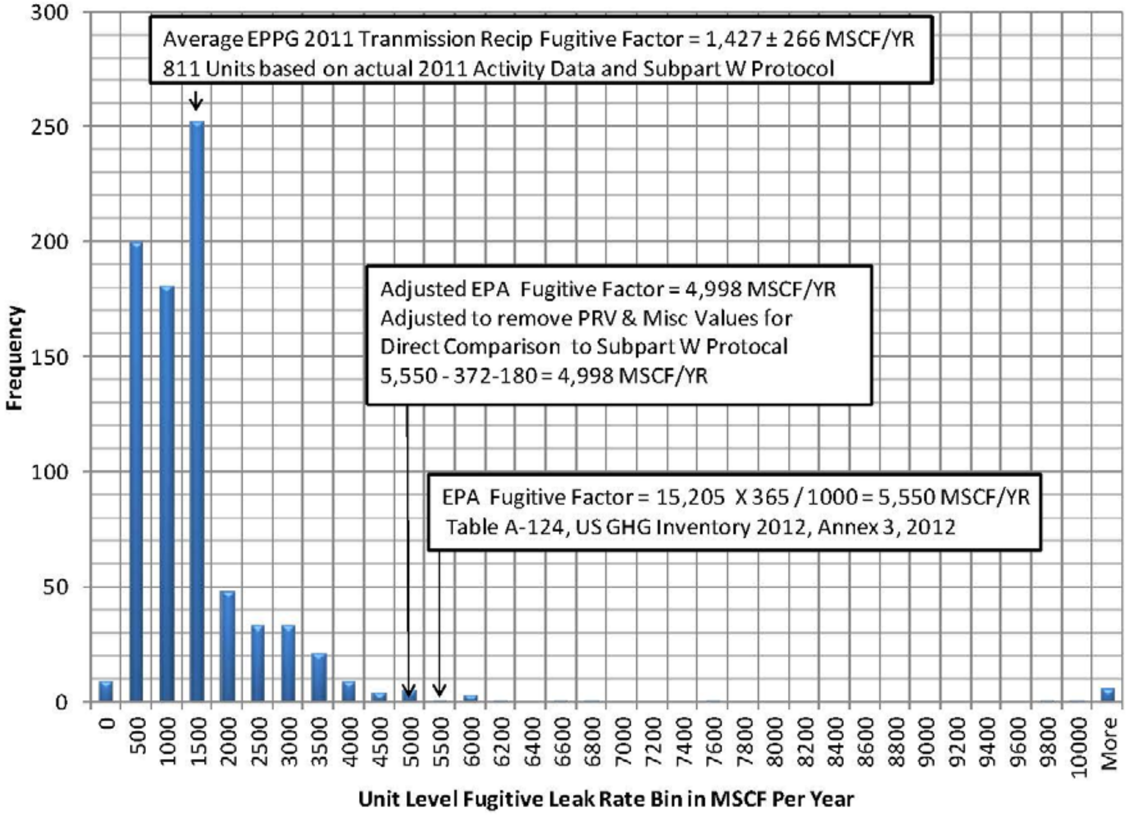


Figure 4: Histogram of El Paso Pipeline Group (EPPG) 2011 Storage Station Reciprocating Compressor Fugitive Emissions in MSCF/YR

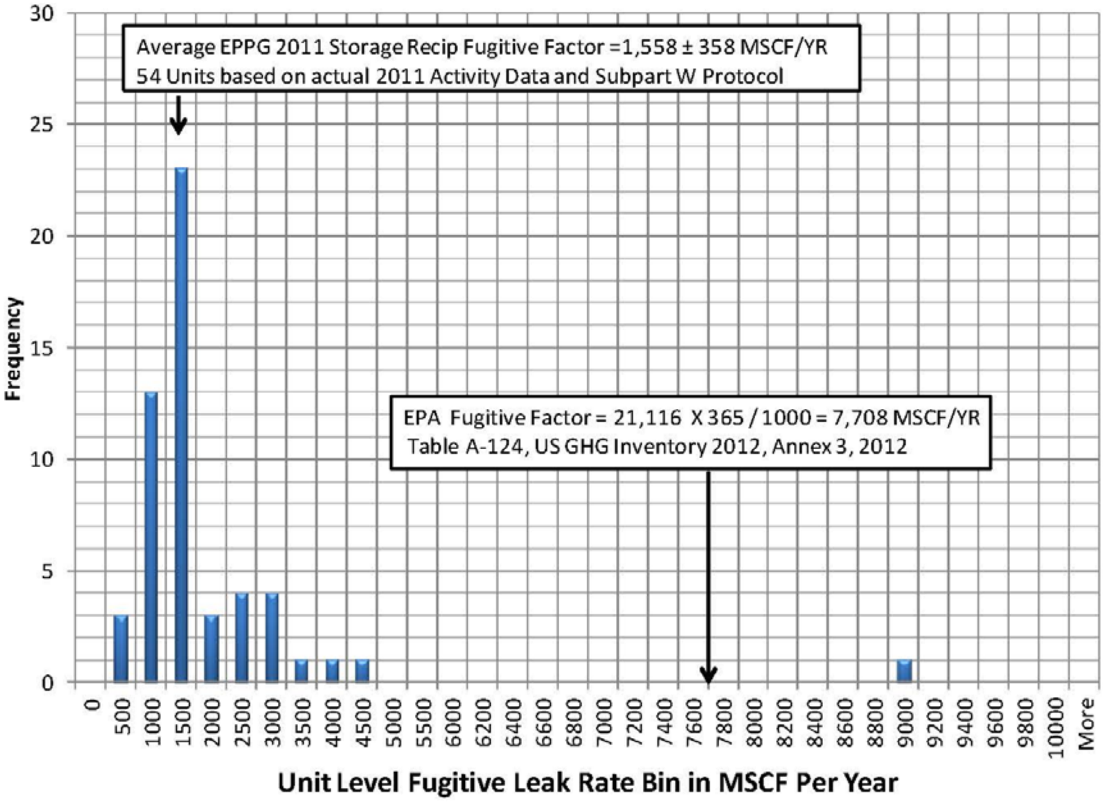


Figure 5: Histogram of El Paso Pipeline Group (EPPG) 2011 Transmission Station Centrifugal (Wet Seal) Compressor Fugitive Emissions in MSCF/YR

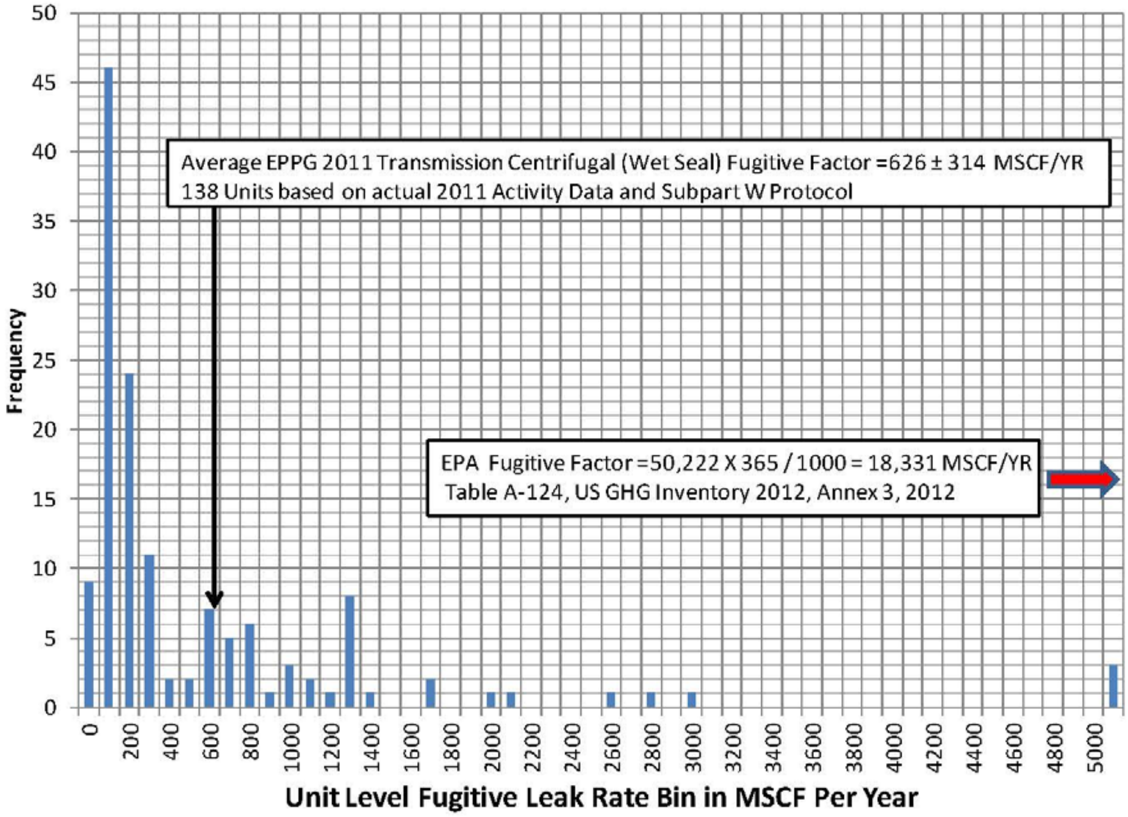
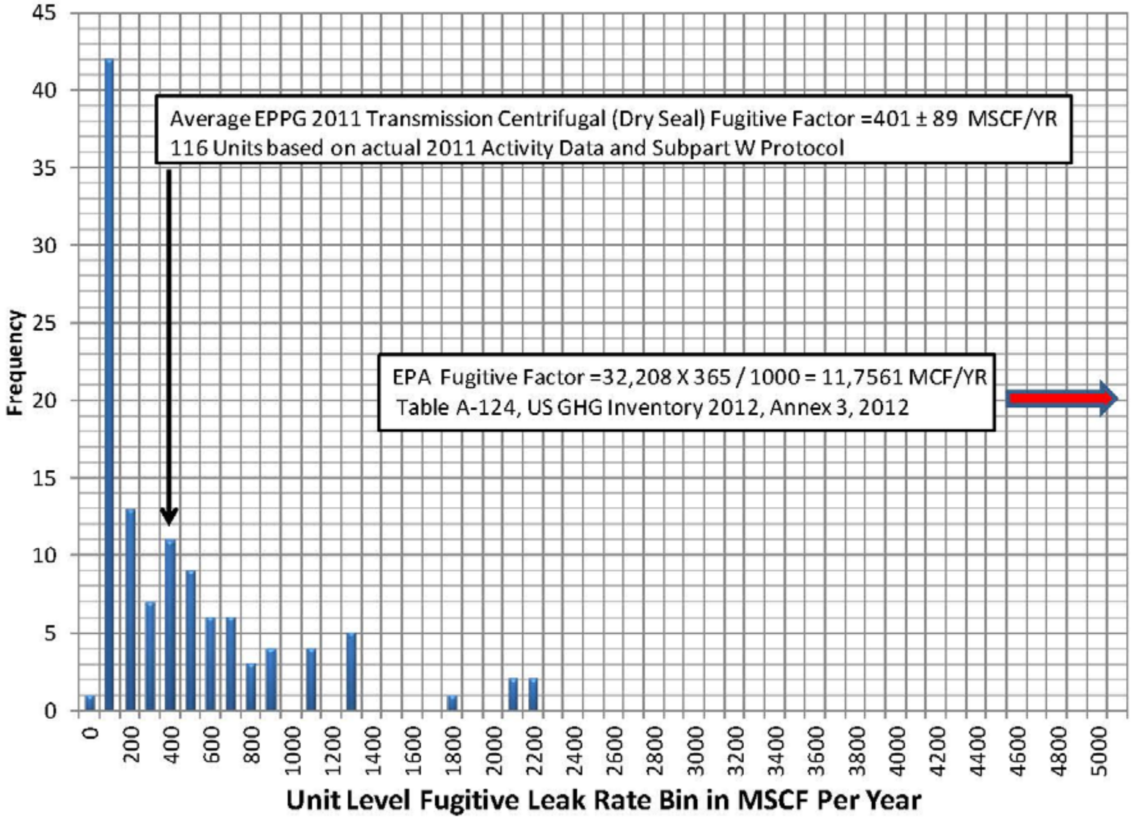


Figure 6: Histogram of El Paso Pipeline Group (EPPG) 2011 Transmission Station Centrifugal (Dry Seal) Compressor Fugitive Emissions in MCF/YR



Average EPPG 2011 Transmission Centrifugal (Dry Seal) Fugitive Factor =401 ± 89 MSCF/YR
116 Units based on actual 2011 Activity Data and Subpart W Protocol

EPA Fugitive Factor =32,208 X 365 / 1000 = 11,7561 MCF/YR
Table A-124, US GHG Inventory 2012, Annex 3, 2012

Commenter: El Paso Corporation

Comment: *While there has been significant focus by various entities on methane emissions, especially related to flowbacks from unconventional well completions and workovers, the largest uncontrolled emission category per the EPA inventory is well clean up (liquids unloading) - an event associated with conventional low-pressure wells. Per the EPA well completions contribute approximately 4% of the total emissions from the combined production, processing and T&S sectors; well clean up contributes approximately 37% of the combined emissions prior to emission controls. Prior to the 2009 revisions, the EPA employed an emission factor of 49,570 standard cubic feet of methane per year from well clean ups and assumed three scaling factors at three points over the time a well is blown down. In the revised methodology, EPA uses data from 25 well sites from 1992 to conclude that 41.3 % of conventional wells require liquid unloading and assumes this as a constant from 1992 to present - despite the trend of shale gas production accounting now for a larger share of the total gas production which should imply a decrease in the liquids unloading at low pressure convention wells. In addition, the EPA uses the 1992 data survey from 25 wells to conclude that there are 38.73 blowdowns per year per well that require unloading – a precision to the second decimal point of the number of annual blowdowns per year per well! As noted in our 2011 comments, the most significant issue with the approach applied to quantify low pressure well clean up emissions, and also a universal issue with the EPA's national inventories, is that the methodologies are not transparent when first uncontrolled emissions are computed and then the reductions reported via voluntary or mandatory mechanisms are backed out. We recommend that the EPA provide separate factors for controlled and uncontrolled emissions, and compute actual emissions using data from Subpart W reports.*

Commenter: El Paso Corporation

Comment: *In our 2009 comments, El Paso provided details related to estimates of emissions from centrifugal compressors. In our comments, we concluded that EPA incorrectly averaged12 the data from a 48 sample data set presented in a World Gas Conference paper (WGC 2009). If an emission factor calculated by using the correct average of the WGC data had been used in the draft inventory, the emissions due to compressor wet seal would be reduced to 58% of the current estimate for processing, 60% of the current estimate for transmission, and 66% of the current estimate for storage. This would have reduced the total inventory for the processing sector by approximately 10.4%, and the total inventory for the transmission/storage sector by approximately 4.2%. To arrive at the dry seal emission factor, the EPA assumed that the midpoint (3 scfm) of the reported Lessons Learned13 range of up to 6 scfm adequately characterized dry seals. Since there are typically 2 dry seals per compressor, the total per-compressor emissions rate from dry seals is 6 scfm. To arrive with a number of compressors using dry seals, EPA's main source was a presentation from 2003 on centrifugal compressors in the natural gas industry14 which showed that 90% of new compressors sold were equipped with* *dry seals. EPA assumed that all centrifugal compressors installed prior to 1992 were equipped with wet seals. Assuming that 90% of new centrifugal compressors since 2003 were equipped with dry seals, and that there were none dry seal compressors in 1992, the EPA interpolated a straight-line estimate of the percentage of new compressors that were equipped with dry seals. That is, the percentage of new compressors equipped with dry seals increased linearly between 0% in 1992 and 90% in 2003.*

Commenter: NAFO

Comment: *The IPCC Guidelines Appropriately Include Emissions From All Woody Biomass Products, Including Energy Feedstocks, in the LULUCF Sector Because They Are Part of the Forest Carbon Cycle*

First, and most importantly, the GHG Inventory – and the IPCC Guidelines on which it is based – recognizes the critical difference between biogenic and fossil CO2 emissions. Biomass that is combusted for energy is part of the natural forest carbon cycle and must be accounted for in a manner that reflects the natural balance between forest growth and harvest. As the GHG Inventory recognizes, carbon "is continually cycled among these storage pools and between forest ecosystems and the atmosphere as a result of biological processes in forests (e.g. photosynthesis, respiration, growth, mortality, decomposition, and disturbances such as fire or pest outbreaks) and anthropogenic activities (e.g. harvesting, thinning, clearing, and GHG Inventory at 7-12. Thus, at the same time that biomass combustion emits CO2 into the atmosphere, replanted and regenerating forests sequester CO2 from the atmosphere. Because the net impact that forest ecosystems have on atmospheric CO2 concentrations depends on the amounts of carbon sequestration and emission that occur over a given time period, it can be measured in an accurate and practical manner by monitoring changes in forest carbon stocks over time.

Recognizing the interrelated nature of the biogenic carbon cycle, the IPCC Guidelines wisely account for all biogenic carbon fluxes – including biomass energy emissions – in the LULUCF sector. This sector includes all terrestrial carbon stocks including forests, croplands, grasslands, and urban areas. By measuring the carbon stocks in each forest carbon pool over time, the IPCC Guidelines permit EPA and other agencies tasked with implementing the United Nations Framework Convention on Climate Change ("UNFCCC") requirements to determine whether carbon sequestration and emissions in the forest sector are balanced. As EPA explained in a previous GHG Inventory:

The combustion of biomass fuels such as wood, charcoal and wood waste and biomass-based fuels such as ethanol from corn and woody crops generates CO2. However, in the long run, the CO2 emitted from biomass combustion does not increase net atmospheric CO2 concentrations, *assuming that biogenic C emitted is offset by the uptake of CO2 that results from the growth of new biomass. As a result, CO2 emissions from biomass combustion have been estimated separately from fossil fuel-based emissions and are not included in U.S. [energy sector] totals.*

EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007 at Energy 3-59, available at http://epa.gov/climatechange/emissions/usgginv_archive.html. The IPCC Guidelines, as described by EPA, accurately reflect the practices of private forest managers, who manage their forests to maintain stable carbon stocks and produce a constant supply of harvestable forest products over an extended period of time. The success of these forest managers in balancing regeneration and harvest is evident in the GHG Inventory as forest carbon stocks have been increasing since the GHG Inventory began in 1990. See GHG Inventory at 7-14-16. Thus, the atmosphere does not see any increase in CO2 concentrations as a result of U.S. forestry practices, even though some forest products are combusted for energy. In contrast, fossil fuels, which are formed on geological time scales, are not part of a natural cycle that operates on climate-relevant time scales and fossil CO2 emissions cannot be naturally sequestered on climate-relevant time scales. Because the combustion of fossil fuels always produces a net increase in atmospheric CO2 concentrations, fossil fuel emissions are appropriately measured within the energy sector at the point of combustion.

Further, the GHG Inventory appropriately recognizes that forest products themselves play an important role in maintaining forests as carbon sinks. As NAFO has previously explained, strong markets for forest products are essential for maintaining or even expanding forest carbon stocks and, in fact, have been responsible for much of the growth in forest carbon stocks over the past half-century. See National Alliance of Forest Owners' Comments to the Science Advisory Board Carbon Emissions Panel (March 16, 2012) at 6-7 ("NAFO SAB Comments") (attached as Exhibit A). But aside from this climate benefit, forest products continue to store carbon for decades after harvest while the products remain in use. Thus it is inappropriate to simply assume that all forest carbon is emitted immediately upon harvest. NAFO fully supports EPA's efforts to model and quantify the harvested forest carbon that is transferred into long-term storage pools and thus does not increase atmospheric CO2 concentrations. By doing so, EPA can more accurately assess what the atmosphere sees as a result of forest management practices in the United States.

Use of the IPCC Guidelines Produces Accurate and Consistent Results with Minimal Transaction Costs and Additional Resource Burdens

Second, reliance on the IPCC Guidelines ensures that the GHG Inventory produces consistent and accurate data that can be used in a variety of policy contexts while providing certainty and apples-to-apples comparisons for key stakeholders. EPA's annual GHG Inventory is produced in accordance with the United State's obligations under the UNFCCC. A primary purpose of the GHG Inventory is to provide a common and consistent mechanism that enables UNFCCC Parties to make comparisons regarding GHG emissions between countries and over time. This *purpose cannot be achieved without the consistent use of a uniform accounting methodology. The IPCC Guidelines have been used both domestically and internationally since the GHG Inventory process began. EPA's continued use of the IPCC Guidelines as the starting point for its accounting methodology will safeguard its past investments in developing the GHG Inventory and ensure that the UNFCCC's goal of creating comparative GHG data will continue to be met.*

Aside from its role under the UNFCCC, the GHG Inventory is an important resource that can be used in the development of domestic policy. As the GHG Inventory explains, "[a] national land-use categorization system that is complete both temporally and spatially" is required to provide accurate comparisons and guide policy-makers. GHG Inventory at 7-4. NAFO agrees that the climate benefits of biomass can be most accurately observed on broad spatial and temporal scales and supports EPA's efforts to expand upon the IPCC methodologies in order to produce "a more comprehensive and detailed estimate of emissions," at appropriately broad spatial and temporal scales. See GHG Inventory at ES-1; see also NAFO SAB Comments at 5-8. NAFO also supports EPA's efforts to improve the accuracy of the GHG Inventory by incorporating improvements in existing databases as they become available. E.g. GHG Inventory at 7-4, 11

The GHG Inventory's reliance on existing data sources also streamlines implementation by avoiding the need for costly and time consuming data collection and analysis. While EPA is certainly capable of developing a single comprehensive approach to accounting for carbon stocks in the LULUCF sector, it has appropriately recognized that all of the necessary data is already being collected at the national level through the US Forest Service's Forest Inventory and Analysis ("FIA") database, the Department of Agriculture's National Resources Inventory ("NRI"), and the U.S. Geological Survey's National Land Cover Dataset ("NLCD"). By relying on national-scale data that is readily available though existing federal databases, EPA has been able to develop an accounting framework at minimal costs to the Agency or the land owners that comprise the LULUCF sector. In this way, the GHG Inventory serves as a model for other federal programs. In fact, EPA has proposed to reply on the same annual FIA data in its Accounting Framework for Biogenic CO2 Emissions from Stationary Sources (Sept. 2011).

While review of this proposed accounting framework is ongoing, NAFO continues to support EPA's use of nationally available data in developing policies for regulating CO2 from stationary sources.

Despite the fact that biomass combustion represents one part of the continuous carbon cycle, some organizations assert that biomass emissions can be measured more accurately and effectively at the point of combustion. These approaches rely on a complicated chain-of-ustody approach that tracks biomass feedstocks from the point of harvest to combustion. Not only would such a complicated chain introduce considerable uncertainty due to its complexity, it would prove practically infeasible due to the significant recordkeeping costs that would be imposed upon EPA, biomass energy facilities, and others in the biomass supply chain. Furthermore, such approaches also run the significant risk of significantly distorting the atmospheric consequences *of biogenic CO2 emissions by applying spatial and temporal scales that are too narrow or that rely on arbitrary and often complex baseline assumptions. There is simply no reason to adopt a more complicated methodology that will produce less accurate results. The GHG Inventory's 20-year track record proves that this national-scale forest carbon stock approach provides practical, accurate, and efficient measurements of the climate impact of the entire forestry sector, including biomass energy.*

Conclusion

As explained above, NAFO supports EPA's use of the IPCC Guidelines in the GHG Inventory. Not only do the IPCC Guidelines produce meaningful data that can be compared over time and across nations, they also distinguish biomass emissions and fossil fuel emissions and demonstrate that biomass is a carbon neutral energy source. Despite some calls for EPA

to adopt a different accounting method for biomass energy combustion, NAFO strongly encourages EPA to continue its current practice of conforming to established international guidelines, which in turn produces accurate and efficient GHG data for the forestry sector.

Commenter: NAFO

Comment: *As NAFO and its members have explained in earlier comments and presentations to the Panel and EPA, critical to NAFO's mission in reducing GHG emissions is supporting the use of biomass as a renewable energy supply that offers important climate and energy security benefits. EPA's decision to reconsider its approach to regulating biogenic CO2 emissions from stationary sources offers an opportunity to encourage the continued development of climate-beneficial bioenergy capacity. It is NAFO's goal that, with the assistance of the Panel's expertise, EPA will develop a regulatory framework that accurately reflects the climate benefits offered by biomass, encourages its continued development, and promotes appropriate distinctions between bioenergy and other types of energy such as fossil fuel combustion. We believe that the Panel can achieve these goals by making recommendations that avoid unnecessary complexity and by using its expertise to apply scientific theories to real- world scenarios.*

First, we applaud the Panel's commitment to distinguishing between scientific and policy questions and leaving the latter category to EPA. However, the Panel need not retreat to the consideration of purely abstract and theoretical issues detached from real world considerations relevant to forest management and bioenergy production. It is not enough for the Panel to verify that a particular model or approach to carbon accounting is scientifically valid at an abstract level. Instead, the model's assumptions must be rigorously evaluated to ensure that they are consistent with the way that forests are managed and biomass energy is actually produced in the United States. When the Panel finds that multiple alternatives accurately reflect the forestry and *forest products sectors and are capable of efficient implementation, it is appropriate to include such an assessment in the final report and allow EPA to make an informed policy choice among such alternatives. At the same time, when, as a result of its experience, expertise, and investigation, the Panel finds that a model's assumptions do not accurately reflect real- world domestic forestry practices, it must include that information in the final report, and recommend against adoption of the model. For example, the Panel should make clear that the assumptions underlying stand-based accounting methodologies, as well as other assumptions or methodologies that constrain temporal and spatial scales, are inconsistent with U.S. forest management practices and thus are inappropriate for inclusion in an accounting framework.*

Similarly, the Panel should not merely defer consideration to EPA of factors and conclusions that can inform EPA's policy decisions. Again, as a result of its expertise and experience, the Panel is uniquely qualified to assess the costs and benefits of various approaches and determine whether they can be successfully implemented from both a technical and practical perspective. The Panel must bring its experience to bear and inform EPA's decision-making process with sound, objective, and reliable information. It is appropriate, after identifying the pragmatic challenges, costs, and benefits of alternative approaches, to defer a legitimate policy choice for EPA with the benefit of the Panel's analysis of the underlying considerations. It is also appropriate for the Panel to conclude that the benefits of an alternative cannot be achieved without increasing transaction costs to the point that the proposal becomes technically or practically infeasible. These circumstances arise, for example, in facility-based chain-of-custody approaches that require the collection of detailed data from countless landowners and suppliers. In such circumstances, the Panel should inform EPA that the alternative is not viable and recommend against its adoption.

Finally, above all, the Panel must strive to reduce uncertainty and complexity. The Panel's conclusions will serve as the foundation for EPA's regulatory decisions, which, in turn, will have a critical and long-lasting influence on the future of sustainable bioenergy in the United States. As the Panel has noted, the Framework proposed by EPA presents "daunting technical challenges" for implementation due to its complexity. Report, at 6. Unfortunately, NAFO remains concerned that the Panel's efforts to provide greater scientific precision and accuracy threaten to increase rather than decrease that complexity. In our prior comments, we provided a series of ways in which the Panel could reduce the complexity of the EPA's proposed regulatory program.2

Those suggestions are summarized below. First, NAFO urges the Panel to limit its analysis to actual rather than hypothetical biomass energy feedstocks in order to develop generally applicable principles that could be applied uniformly to all biomass energy feedstocks without introducing complex analyses into the regulatory framework. Second, we urge the Panel to focus on spatial and temporal scales that are relevant to U.S. forestry practices in order to avoid complex analyses that are simply irrelevant to biomass energy production. Third, we urge the Panel to avoid consideration of factors that are beyond the scope of EPA's regulatory review.

Fourth, we urge the Panel to accept the limits of science in resolving uncertainty and avoid recommending impractical data collection processes that produce diminishing returns in improved accuracy. After reviewing the revised Report, it is clear that the Panel has addressed some of these suggestions and has made efforts to reduce the complexity in its recommendations. However, on the whole NAFO remains concerned that the recommendations still are so complex that, if adopted, they unfortunately would have the perverse effect of discouraging or foreclosing the development of biomass energy due to the high transaction costs of compliance.

By applying the principles described above and focusing on the pragmatic realities of the forestry and biomass energy sectors, NAFO believes that it is possible to develop a simple and straightforward approach to accounting for biogenic CO2 emissions from woody biomass that can be efficiently and effectively implemented. As described below, such an approach would be based on three threshold determinations, as informed by scientific theory and an understanding of the forestry and biomass industry sectors: (1) the adoption of a national scale; (2) a reference point baseline; and (3) a 100-year time scale. Once these three principles are adopted, the Report's conclusions will properly inform EPA on appropriate and scientifically sound alternatives, including the option of a categorical exclusion for biogenic CO2 emissions. While a conclusion on how to treat biogenic emissions in a regulatory regime ultimately entails some policy choices for EPA, this recommended approach will enable EPA to make sure decisions based on the strongest possible scientific and technical considerations and, for that reason, should be included in the Panel's recommendations to EPA.

Biogenic CO2 Regulations Must Be Based on a National Scale

Before an accounting methodology can be developed, there are a number of threshold issues which must be resolved, including the appropriate spatial scale for regulations. A national scale is the only alternative identified by EPA and the Panel that is supported by science, consistent with actual U.S. forest management practices, and practical to implement. While the ultimate selection of a spatial scale may entail policy considerations, the strong scientific and technical support for a national scale warrants its inclusion in the Panel's recommendations to EPA.

A Broad Spatial Scale is Required to Reflect Domestic Forest

Management Practices

In order to properly reflect the way in which forests are managed and biomass feedstocks are produced, the Panel must recommend and EPA adopt a broad spatial scale. Because the goal of forest management is to produce a continuous supply of forest products, it is fundamentally inconsistent with forestry practices to isolate a single stand and arbitrarily choose a starting point for the carbon cycle. By choosing to start the carbon cycle at the time of planting or harvest such an approach creates an arbitrary carbon credit or debt.3 While it is theoretically valid to view the carbon cycle in a linear fashion, tracking the movement of a single carbon atom or the carbon stocks on a single plot of land, this approach is inconsistent with the way that *forests are managed in the United States. Thus, even if the stand-based accounting principles included in Walker (2010) and Biomass Energy Resource Center (2012) are scientifically valid in an framework as their primary assumptions are at odds with the established practices of the forestry sector as a whole.*

Forest owners and managers do not treat each stand independently, but instead develop broad management plans at a landscape level. These plans are designed to produce diverse age classes and a constant supply of harvestable forest products over an extended period of time. As a result, the processes of CO2 emission and sequestration occur simultaneously within the landscape. Therefore, as NAFO has previously explained, the emissions associated with harvesting are offset on a continuous basis by regeneration that is occurring on the many other stands that are not harvested and forest stocks remain stable. By focusing on the simultaneous emissions and regeneration, it is also apparent that a broad spatial scale is consistent with the science of the carbon cycle. While the carbon cycle is often viewed linearly, focusing on the growth, harvest, and regeneration of a single tree or stand, it can also be viewed in a single temporal plane as emissions and regeneration take place in different portions of a single, managed landscape. Thus adopting a broad spatial scale would be consistent with both the science of the carbon cycle and domestic forest management practices.

In the same manner, the forest products industries – including biomass energy – are integrated at a national level as individual producers also obtain supplies from a vast and ever-changing array of forest owners and suppliers.6 Moreover, the producers compete with each other in the marketplace making it impossible to isolate impacts on small spatial scales. Indeed, as the Panel noted, a national scale is necessary to model forestry markets and the economic behavior of landowners. Report at 32-35. Thus, individual forest owners continually respond to market signals that are sent at national or even global scales, and shift their plans in anticipation of and response to new market demands. While geographic constraints may fix the location of forests and biomass energy facilities, the markets that they serve are unconstrained and treat all forest owners and suppliers equally. Thus, both market demands and the response from forest owners is best captured at a national scale. Indeed, this relationship can be readily observed in historical data as forest owners have repeatedly responded to new market demands, increasing national forest carbon stocks in the process. Thus, the nature of forest products markets also requires that biogenic CO2 emissions be considered on the broadest scale possible.

A National Scale is the Most Appropriate Choice Among Broad Scales

A national scale is clearly superior from a technical standpoint among other options such as a broad landscape-based spatial scale. First, a national scale responds most closely to the global nature of climate change and EPA's regulatory authority under the Clean Air Act to implement air policies at a national level. Thus, it avoids the problems of scale sensitivity and domestic leakage that plague regional approaches. See Report at 6. It also has the advantage of treating all biomass facilities equally and allowing market forces to dictate their location based on *considerations such as supply, demand, and market efficiency. Second, a national scale will prove the most practical, predictable, and least burdensome approach to implement. As EPA and NAFO have noted, data from the U.S. Forest Service's Forest Inventory and Analysis (FIA) program and other sources are readily available and can be incorporated into a regulatory framework at little cost to EPA or the regulated entities. Framework at 31-32. Thus adopting a national scale would serve the important purpose of reducing complexity and transaction costs and thereby promote climate-beneficial biomass energy.*

The application of a national scale is also consistent with the Panel's own recommendations in its discussion of alternatives. The Panel's endorsement of the development of default BAFs for feedstock categories as an alternative to facility- specific BAFs would necessarily be applied at a national level. Report at 45. While the necessity of distinguishing among feedstocks is addressed below, the Panel's inclusion of this alternative shows that a national, rather than facility-based, approach to accounting for biogenic CO2 emissions is consistent with scientific theory and would be appropriate in practice.

While EPA might consider the alternative of incorporating a broad spatial scale by adopting a facility-based fuelshed approach, this does not withstand close scrutiny of sound science or pragmatic forest management considerations. As NAFO has previously explained, while a facility-based approach would theoretically allow EPA to treat each biomass facility independently for attribution purposes, such an approach would prove technically and practically infeasible. First, applying such an approach at the landscape level would be technically infeasible as individual facilities have overlapping fuelsheds and obtain feedstocks from a vast and constantly changing array of landowners. Thus there is no way to distinguish between facility fuelsheds based on geography. The only alternative would then be a complex stand-based chain-of-custody approach, but such an approach would prove practically infeasible due to the high transaction costs.

While the selection of a spatial scale ultimately entails some policy considerations by EPA, such policy decisions must be supported by reliable, credible, and sound scientific conclusions. Under that standard, it is not a choice where all options are equal. As the Panel recognizes, a national scale offers a number of important benefits that could ensure that the final regulations adopted by EPA can be successfully implemented. Having noted the shortcomings in EPA's proposed regional scale, Report at 26-27, the Panel should likewise assess the alternative choices and inform EPA of its conclusions. NAFO is confident that, if the Panel were to do so, a national scale approach would emerge as the only alternative that is fully supported by scientific and technical considerations and capable of efficient implementation.

A Reference Point Baseline Must Be Adopted Because No Other Alternative Is Capable of Implementation

One of the most challenging issues related to the development of an accounting framework for biogenic CO2 emissions is the selection of a baseline. After considering several alternatives, EPA selected a reference point baseline because it provided "a straightforward way to assess an individual stationary source's emissions using existing data." Framework at 42. NAFO supports this conclusion as a sound policy decision. In contrast, the Panel has proposed an anticipated future baseline that seeks to isolate the positive impact of biomass energy and determine what would have happened in the absence of additional biomass energy demand. Despite its theoretical logic, the Panel's attempt to describe such an approach only confirms the inherent complexity associated with anticipatory future baselines and demonstrates why EPA's straightforward and accurate approach must be applied.

As NAFO has noted in previous comments to the Panel, it is virtually impossible to isolate the impact of biomass energy and determine what would have happened without demand for biomass energy. In reality, biomass energy is a small segment of the forestry sector and is intimately related to other forest products in both time and space. First, in most cases, biomass is not produced and harvested as a separate product for energy production. Instead, the forestry residues and milling residuals that are combusted for energy represent co-products that are produced alongside more valuable primary products. Indeed, even when roundwood is harvested and used directly for biomass energy, it is harvested as part of a thinning process that is designed to improve the quality of the remaining trees that will be harvested later for other, more valuable forest products. It is simply not economical to grow and harvest mature trees for energy. Instead, biomass co-products provide incremental economic value to the forest owner producing subtle, yet important, market signals that encourage biomass production and increase forest carbon stocks. As a result of this close relationship between forest products and the long time frames over which forest rotations occur, there is no simple and straightforward way to strip out biomass energy demand and determine what would have happened in its absence.

As the Panel is well aware, developing an anticipated future baseline is a daunting, although ultimately unnecessary, task. The approach described in the revised Report, which seeks to "combine the economic behavior of landowners with the associated dynamics of forest management and growth while allowing for competing uses of land for forestry, agriculture, and other activities," Report at 33, is a marked improvement over the approach described in the initial report. Importantly, this approach seeks to account for the decision-making processes of forest owners and reflects the anticipatory nature of investments in forests. Report at 34-35. By doing so, it moves closer to identifying and attempting to account for all of the factors that can influence forest management decisions and the quantity of forest carbon stocks.

But even the inclusion of anticipatory investments and other market forces is not enough to produce a comprehensive model of the impact of biomass energy. As the Report notes elsewhere, the purpose of an accounting methodology is to account for the changes that "the atmosphere sees" as a result of biogenic CO2 emissions from stationary sources. E.g., Report at 15. But as currently formulated, the Panel's anticipated future baseline only considers what the *forest sees, as it focuses solely on “changes in forest stocks.” Id. at 2.3. This ignores the primary climate benefit of biomass energy – the displacement of fossil fuel emissions. Thus, the assertion that “a reduction in the rate of increase of carbon stocks is equivalent to an increase in emissions,” id. at 4, is incorrect. A reduction in the rate of increase in carbon stocks that results in a reduction in fossil fuel emissions could actually reduce total emissions. In other words, the anticipated future baseline described by the Panel, which is already hopelessly complex, must either become even more complex in order to accurately reflect what “the atmosphere sees” or remain fundamentally flawed for failing to fully capture the carbon cycle associated with forest-based biomass energy.*

Further, the adoption of an anticipated future baseline would raise significant legal concerns and add uncertainty to the implementation process. By requiring forest owners to continue to increase forest carbon stocks at current rates, applying an anticipated future baseline to stationary source regulations would transform what is a voluntary, climate-friendly practice into a mandatory duty. If such a regulatory program were in place the baseline could also be applied elsewhere, for example in carbon offset programs. If these regulatory programs make carbon sequestration a mandatory duty concerns associated with an anticipated future baseline would add further uncertainty and make implementation even more difficult.

In light of this complexity, and ultimately the uncertainty surrounding these future projections, see Report at 35-36, it was certainly appropriate for EPA to propose a reference point baseline. While it cannot entirely isolate the impact of biomass energy, a reference point baseline does describe what “the atmosphere sees” as a result of the forestry sector as a whole. As EPA recognized in the Framework, as long as forest carbon stocks are stable or increasing, the atmosphere does not see any increase in CO2 concentrations as a result of the forestry sector. Framework at 25-26.16 Indeed, when fossil fuel displacement and long-term storage in forest products are considered, the atmosphere is likely to see a reduction in CO2 concentrations when forest carbon stocks remain stable.

This is not to say that the predictive models referenced by the Panel have no purpose, but only that they are too complex, uncertain, unmanageable, and inaccurate in their current form to be included as a part of a regulatory program. Given these concerns over implementation, the Panel should support EPA’s conclusion that a reference point baseline is appropriate and instead recommend ways that EPA can use these predictive models to monitor forest carbon stocks and perhaps refine its regulatory approach over time.

The Climate Impact of Biogenic CO2 Emissions Must Be Assessed on a Policy-Relevant 100-Year Time Scale

Finally, as the Panel appropriately recognizes, the selection of a time scale is an important policy decision that will have a significant effect on the final regulations adopted by EPA. But, despite the Panel’s clear preference for a 100-year time scale see Report at 10-13, it declines to *make a recommendation, asserting instead that the choice of time scales is a policy decision that must be resolved by EPA, Report at 44.*

While there are certainly tradeoffs between different time scales, sound science reflecting pragmatic considerations squarely favors a 100-year time scale. While other time scales may also be scientifically correct, Report at 11, only a 100-year time scale is consistent with EPA's regulatory goals, domestic forestry practices, and the administration's mandate promoting climate-beneficial renewable energy.

First, a 100-year time scale is consistent with EPA's regulatory goals for biogenic CO2 emissions. EPA decided to defer regulation of biogenic CO2 emissions, in part, to "conduct a study of the science surrounding biogenic CO2 emissions and their role in the carbon cycle." 76 Fed. Reg. 43,490, 43,499 (July 20, 2011). Further, to understand how biogenic CO2 emissions affect the climate, the time scale must help explain what "the atmosphere sees" as a result biogenic CO2 emissions. A 100-year time scale can answer these questions. First, as the Panel notes, climate modeling studies have demonstrated that "the peak warming in response to greenhouse gas emissions is primarily sensitive to cumulative greenhouse gas emissions over a period of roughly 100 years, and is relatively insensitive to the emissions pathway within that timeframe." Report at 11. Thus adopting a 100-year time scale will allow EPA to consider the biogenic carbon cycle over time periods that are relevant to the global climate system. In contrast, as the Panel notes, shorter time periods such as those relied upon by Walker (2010) and others, focus on irrelevant intermediate time scales and do not provide an appropriate analysis of the biogenic carbon cycle because these intermediate effects prove transient and disappear over longer time scales. Report at 11.19

Second, a 100-year time scale is consistent with the manner in which forestry is practiced in the United States. As the Report notes "it is important to consider the turnover times of different biogenic feedstocks in justifying how they are incorporated into the framework." Report at 10. Although, as described above, the forest carbon cycle is best considered spatially on a landscape scale, it is nevertheless instructive to also consider it in a linear fashion for purposes of conducting a thorough scientific review. While in theory it would be possible to adopt a different time scale for each feedstock corresponding to its turnover time, such an approach is unnecessary as few, if any, forests are managed with turnover times longer than 100 years. Thus by adopting a 100 year time scale, EPA would simplify the regulations while ensuring that, for any given feedstock, the landscape would have turned over at least once during the relevant time period and avoid the potential for short-term, transient carbon fluxes that could skew the analysis of the carbon cycle. In contrast, if a shorter time period – on the order of 30 to 50 years – were adopted, some feedstocks may not undergo a complete turnover during the study period. Thus, a 100 year time scale offers a simple, uniform approach to carbon accounting that is consistent with forestry practices.

Third, adoption of a 100-year time scale will provide appropriate incentives for biomass energy that are consistent with the administration's commitment to promoting renewable fuels, such as biomass.20 As the Panel recognizes, the climate benefits of biomass, as compared to fossil fuels, become more pronounced as time scales increase. Report at 13. In other words, as NAFO has explained, the climate benefits of biomass energy continue to grow over time as each successive rotation used for biomass displaces more fossil fuels. While a time scale of 100 years is likely sufficient to create the incentives needed to promote biomass energy, shorter time frames may have the perverse effect of discouraging biomass energy due to the differences in energy produced by equivalent amounts of biomass and fossil fuels. Thus, adopting a shorter time frame that discourages biomass energy produces the wrong kind of tradeoffs as it would lock in the continued combustion of fossil fuels in lieu of biomass, despite the recognized long term benefits biomass offers.

Recommendations for a Regulatory Approach to Biogenic CO2 Emissions

In the event that a national scale, reference point baseline, and 100-year time scale are adopted, EPA can develop a scientifically accurate, predictable, and straightforward regulatory framework for woody biomass. First, within this framework, a categorical exclusion can be implemented as a practical matter because domestic forest management practices and sound science demonstrate that biomass energy will not result in a net increase in atmospheric CO2 concentrations on a policy-relevant spatial or temporal scale. Second, the continued applicability of the categorical exclusion will depend solely on the continued use of sustainable forestry practices, which can be monitored on a continuous basis through the comparison of carbon stocks over time.

A Categorical Exclusion is Appropriate as a Practical Matter as Woody Biomass Feedstocks Do Not Increase Net Atmospheric CO2

Concentrations

When considered in the context of a national spatial scale and 100-year time scale, the scientific conclusions in the Report fully support a categorical exclusion for biogenic CO2 emissions from woody biomass, even if such position cannot be accepted a priori. As NAFO noted in its previous comments, the Panel must rigorously test and apply the best science to determine the climate impacts of biogenic CO2 emissions, but must do so with the goal of producing an accounting framework that is simple to implement and provides reasonable certainty to EPA and stakeholders. As NAFO previously observed, this can be accomplished by using sophisticated scientific models to confirm broadly applicable regulatory approaches. Indeed, the Panel has already started down this path by endorsing feedstock-based BAF values as an alternative to facility-specific BAFs. However, this recommendation does not go far enough. Taken to its logical conclusion, it supports a categorical exclusion for woody biomass as all feedstocks derived from woody biomass would have a BAF of zero.

First, when the carbon cycle is applied on a national spatial scale, a categorical exclusion is warranted because carbon stocks are stable and are expected to remain so for many years to come. Unless and until carbon stocks decline on a national scale, there will be no net biogenic CO2 emissions from woody biomass because emissions will be balanced by carbon sequestration on a regular and continuous basis. As the Panel is aware, projecting forest carbon stocks far into the future is fraught with uncertainty, but even the most conservative models suggest that domestic forests will remain a net carbon sink for decades into the future. Since the near-term trajectory of forest carbon stocks remains positive, it makes no sense to incorporate complex regulatory processes to address hypothetical concerns about events that may happen decades into the future. A more prudent approach is to incorporate a monitoring program, as described below, so that EPA can , if necessary, modify its regulatory approach in the future.

Second, the Panel's own analyses based on a time path of decay or recovery confirm that biomass energy will not increase net atmospheric CO2 concentrations over the relevant temporal and spatial scales. As discussed above, peak warming is insensitive to short-term carbon fluxes that occur on time scales shorter than 100 years. Report at 10-13. Thus, the question that the Panel, and ultimately EPA must answer is which, if any, biomass feedstocks that are used (or are expected to be used) for biomass energy will increase atmospheric CO2 concentrations over time scales that exceed 100 years. There are none.

In this Report the Panel reverses course and asserts that forestry residues are not "anyway emissions" when combusted for energy because they do not decompose instantaneously. Instead, the Panel asserts that forestry residue emissions must be modeled through a complicated process that estimates a time path of decay. Report at 18-20 & App'x A. Even if the Panel's approach were accepted in theory, it is simply irrelevant when considered on an appropriate time scale. Regardless of the type of forestry residue considered, these models show that decomposition would be nearly complete after 100 years. Thus emissions from forestry residues are "anyway emissions" on a 100-year time scale, and there is no net increase in atmospheric CO2 concentrations as a result of the combustion of these feedstocks. As a result, a categorical exclusion for forestry residues is warranted.

Further, as NAFO has previously explained, a regulatory approach that promotes biomass energy is likely to increase, rather than decrease forest stocks by creating incentives for individual landowners to maintain or even increase forested acres. NAFO Deferral Rule Comments at 3-4; NAFO December SAB Panel Comments at 2. Even if domestic forests were to become a net carbon source, the appropriate regulatory response is far from certain. For example, to the extent that the change is attributable to stochastic events such as fires and disease or increased urbanization, EPA may conclude that it need not alter its approach to regulating bioenergy.

By the same token, the scientific models endorsed by the Panel for evaluating the time path of recovery for long-recovery feedstocks confirms that these products will produce no net change in *atmospheric CO2 concentrations on policy-relevant time scales. Here, the Panel relies primarily on Cherubini (2012) and the GTPbio factor.26 As the Panel notes, under Cherubini's model this factor initially increases after harvest, but for all feedstocks used in biomass energy, it will return to zero within 100 years. Report at 11-13. Thus, these models confirm that the biomass feedstocks that are currently used (or expected to be used in the future) will have no effect on peak warming and, on policy relevant time scales, will not alter what "the atmosphere sees." Because there are few, if any, commercial forests managed on time scales longer than 100 years, all woody biomass would have a BAF of zero, meaning that a categorical exclusion would also be warranted for long-recovery feedstocks.*

Thus, contrary to the Panel's current recommendations, which would require the application of a time path of decay or recovery for all woody biomass, Report at 11, 18- 20, 44 a categorical exclusion can be applied instead. This demonstrates a fundamental flaw in the Panel's recommendations, which is not supported by the content of the Report. In the Report, the Panel appropriately recognizes that the relevance of these time path functions is dependant on the time scale, and that concepts such as carbon debt are not relevant when long time scales are considered. Report at 11. Thus, while these concepts, without doubt, are valuable tools for understanding the carbon cycle and the impact of biogenic CO2 emissions on net atmospheric CO2 concentrations, there is no a priori basis for including them in a final regulatory framework as the Panel suggests. Instead, as NAFO has previously suggested, these models can simply be used to confirm that, under all circumstances and for all feedstocks, biomass energy does not increase atmospheric CO2 concentrations. While NAFO urges the Panel to replace its current recommendations with a categorical exclusion for woody biomass, the Panel should, at a minimum, note that its recommendations to incorporate time paths of decay and recovery are in fact scale dependent and provide alternative recommendations that can be incorporated if EPA chooses to adopt a longer time scale.

Continuous Monitoring Program Can Be Used to Ensure that Forest Carbon Stocks Remain Stable Over Time

While a categorical exclusion is supported by the science included in the Panel's Report, it is also based upon the fact that forest carbon stocks are – and will continue to be – stable or increasing. Given the critical role that sustainable forestry practices play in supporting a categorical exclusion, it would be appropriate to include a monitoring component into a regulatory framework to ensure that current trends continue. This is what EPA proposed by requiring short-term comparisons of carbon stocks over time. Framework at 25-26.

Contrary to the Panel's assertions, continuous monitoring using, for example, annual FIA data is not inconsistent with the adoption of a 100-year time scale as the two time frames address different issues. The 100-year time scale addresses the relevant time period over which emissions should be considered. But the assumption that there will be no net increase in *atmospheric CO2 concentrations is implicitly dependant on the fact that the forests under consideration will be managed sustainably. Indeed, the*

Panel recognizes this in its alternative proposal for a certification program based on carbon neutrality and "sustainability" principles. Report at 7, 45-47.29 Thus, even under a 100-year time scale, a monitoring approach is needed to ensure that forestry is practiced sustainably and that harvested stands are regenerated.

While the monitoring approach included in EPA's Framework is national in scale and cannot establish stand-based linkages, that is not necessary to demonstrate sustainability over time. A national scale approach that incorporates annual FIA data offers a practical and cost effective method to ensure that forestry is practiced sustainably in the aggregate. While small changes can take place on the stand level as individual owners make management changes, a national scale monitoring system will ensure that, as a whole, forestry is practiced sustainably and that there is no net increase in atmospheric CO2 concentrations as a result of biogenic emissions from woody biomass. By including such a monitoring system, EPA can implement a categorical exclusion with the assurance that it can take further regulatory action if the factual circumstances supporting a categorical exclusion change.

Conclusion

NAFO continues to support EPA's decision to seek an independent peer review of its proposed accounting methodology for biogenic CO2 emissions and applauds the Panel's efforts to assess this complex field. We urge the Panel to keep implementation at the forefront as it formulates its recommendations and hope that our comments will assist the Panel in identifying means to simplify its final recommendations to EPA. NAFO is standing by to provide further information or answer any questions that the Panel may have.

Commenter: Center for a Competitive Waste Energy

Comment: *Include in the table showing each sector's responsibility for anthropogenic greenhouse gas emissions the applicable value when current instead of obsolete Global Warming Potential multipliers are used.*

To use a GWP for methane in 2010 of 21, when the most reliable value today is 62% greater, has the effect of grossly undercounting the impacts of sources of anthropogenic methane emissions compared to sources of other greenhouse gases. That cannot but gravely distort society's response to a much more serious threat and result in a misapplication of resources to avert climate change, especially in the context of near-term impacts described next.

Therefore, we recommend that the final inventory include the existing table that shows a consistent time series from 1990 to 20008 (as modified by the other comments that follow below) *to comport with the Guidelines. But, then the table should include an additional right-hand column showing the 2008 data converted to the current data on GWPs. Nothing in the Guidelines precludes or discourages more accurate supplementation.*

There is an enormous value in incorporating the most reliable data into decision-making, and the Draft fails to accord this need its due. If the definition of "authoritative" were somehow to be twisted to mean "hopelessly out-of-date," the practical utility of the entire exercise would be called into in question and resemble nothing so much as "fiddling while the world burns." The difference between 1996's very preliminary state of knowledge then, which was largely ignorant of methane's indirect effects, and today, more than 15 years later, is simply too great to ignore on the grounds of nothing more substantive than bureaucratic inertia.

Each GHG has a different residence time in the atmosphere before they decay or are absorbed, from 0.38 years for methylene chloride to 50,000 years for PFC-14, with 12 years for methane. In order to equate each GHG to CO , the same residency must be assumed to perform the calculation, even though, in fact, the gases remain airborne for vastly different periods. The current convention for that common denominator is 100 years, which initially was the proxy for CO2's duration in the atmosphere.

However, global warming does not proceed linearly over time, but rather, accelerated by positive feedback loops, changes in climate can ramp up rapidly and irreversibly in the near term as tipping points are crossed.7 In response to this implacable reality, a growing body of scientific opinion has more recently urged a two-pronged strategy to address those points of no return. This is not to suggest either ignoring or demoting the long-term consequences. Rather, the recommendation is only to recognize that, in order to sustain the viability of human institutions until that far-off day arrives, we must first insure that quick action is taken to avert crossing key tipping points, after which further remedial action is no longer possible:

"Policy must evolve and incorporate the emerging science in order to be effective. There is a growing need to create a two-pronged framework capable of not only mitigating long-term climate change but also managing the magnitude and rate of change of near-term R[adiative] F[orcing]. Short-lived pollutants (black carbon and tropospheric ozone) and medium-lived pollutants (methane) account for more than half of the positive RF generated in years 1 to 20."

Once the need for such a two-pronged strategy is understood, then attention quickly turns to methane as the most important GHG for that approach, as Dr. Jackson alludes to in his above statement. According to climate scientists at the National Aeronautics and Space Administration (NASA), the combination of methane's warming potency, and its short lifetime in the atmosphere, plays an especially critical role in the near term when we confront those critical tipping points. Methane's residency is 12 years, and, when measured in the next 20 instead of 100 years, is 105 times as powerful as CO2:

"[F]easible reversal of the growth of atmospheric [methane] and other trace gases would provide a vital contribution toward averting dangerous anthropogenic interference with global climate. [Methane] deserves special attention in efforts to stem global warming. Given the difficulty of halting near-term CO2 growth, the only practical way to avoid [dangerous interference] with climate may be simultaneous efforts to reverse the growth of [methane].

Similarly, Robert Watkins, the co-chair of the IPCC's Third Assessment, recently wrote in the disappointing aftermath of Copenhagen:

"This month's Copenhagen talks focused on the leading climate change culprit: CO2. But reversing global temperature increases by reducing carbon emissions will take many decades, if not centuries. Even if the largest cuts in CO2 contemplated in Copenhagen are implemented, it simply will not reverse the melting of ice already occurring. The most obvious strategy is to make an all-out effort to reduce emissions of methane. Methane's short life makes it especially interesting in the short run, given the pace of climate change. If we need to suppress temperature quickly in order to preserve glaciers, reducing methane can make an immediate impact. Compared to the massive requirements necessary to reduce CO2, cutting methane requires only modest investment. Where we stop methane emissions, cooling follows within a decade, not centuries. That could make the difference for many fragile systems on the brink."

Indeed, EPA, itself, has long observed methane's critical importance for addressing short term climate impacts:

"This relatively short lifetime makes methane an excellent candidate for mitigating the impacts of global warming because emission reductions could lead to stabilization or reduction in methane concentrations within 10-20 years."

For these reasons, we strongly urge the Draft to include an additional chapter on short- term impacts (i.e. the next twenty years), along with the 100-year inventory values, and the GWP factors that are applicable to that time frame, along with reference to the greenhouse gases most important to short term climate action plans. In the case of methane, as noted, that would be a multiplier of 105 times CO2's warming potential when using the latest data, and 72 times CO2's, when using the data from AR4. This would enable decision-makers to assess where their short-term climate action plans should be most effectively directed.

This additional supplementation also comports fully with the IPCC protocols. The Second Assessment stated that while the UN Framework held there should be one set of consistent 100 year based GWP values across reporting nation's inventories, it also specifically provided that "[p]arties may also use other time horizons."

As discussed in Chapter 8 of the Draft, along with Annex 3.1, landfills are among the significant sources of GHGs associated with climate change, because organic discards, which are half or more of total discards, if not separated at the source, are most often buried. In the oxygen-

starved environment of a sealed landfill, food scraps, soiled paper, grass clippings, leaves, brush and other organic matter decompose anaerobically under the influence of methanogenic microbes. These thrive in the absence of oxygen, and create methane as a byproduct of decomposition.

Because modern lined landfills can extend for hundreds of acres in extent and rise hundreds of feet above grade, gas generated inside the waste body flows out into the atmosphere through myriad routes that defy measurement. This includes not only through cracks, tears and broken seams at the surface and along the sides and top, but also conveyed along the bottom of a facility following leachate collection gravel trenches and piping, wherever there is a path of least resistance.

In an attempt to overcome this lack of data, the process underlying the Annex's description purports to use the following mass balance equation that is calculated for each year:

(1) $$\left| \text{Gas released} = \text{Gas generated} - \text{Gas captured} - \text{Gas oxidized} \right|$$

As discussed below, the problems with this attempt to represent reality are:

(1) Incorrect Modeling. Only one of the three terms to the right, Gas Captured, is known. Two are only modeled, not observed, values, namely Gas Generation and Gas Oxidized.15 To estimate the unknown Gas Generation in order to then estimate Gas Released, a model is used which is inapplicable to the particular and unique conditions of a lined landfill and fails to include a coefficient for the most critical independent variable involved in decomposition of buried wastes, the level and distribution of essential moisture. Moreover, many of the landfill input data appears to be incorrect.

(2) Incomplete Landfill Phases. Gas generation from wastes interred today continue for decades into the future at a rate that varies with five different phases in a landfill's life that affects the level and distribution of essential moisture, all of which is ignored by the Draft's methodology.

(3) Oxidation Misapplied. The studies used to estimate oxidation are inapplicable to lined landfills.

Most of the controverted modeling turns on the equation used in the Draft to estimate Gas Generated, which is explained first.

EPA first estimates the amount of annual Gas Generated based upon modeling by using a First Order Decay (FOD) equation, which in its simplified form is expressed:

(2) $$Methane = \sum_{i=1}^{n} M \times L_o \times k \times e^{-k \times t_i}$$

Unfortunately, this simplified model, and all of its variants, was derived from, and is only applicable to, a continuous decay phenomena acting upon a declining mass, where the decay rate is independent of the availability of limiting pre-conditions that otherwise would impede particle disintegration. An example would be the radioactive decay of a uranium isotope that is represented by a constant decay rate multiplied by the mass, which declines each year as the original mass is reduced by the prior year's decay.

Moisture pre-condition. Anaerobic decomposition in a landfill suffers far too many complications for such a simplified model to be valid. In particular, first, as discussed in this section, the model does not account for whether the distribution and quantity of essential moisture is adequate to sustain the near optimal levels of decomposition assumed by the model. Yet, inexplicably, the Draft's list of relevant factors for methane formation ignores the necessity for their being very high moisture levels.

Along with heat, microbes and pH, which generally are not limiting conditions, decomposition in a landfill cannot comprehensively proceed as the model predicts unless there is a continuing adequate supply of moisture greater than 50%. However, the entrained moisture in the incoming wastes is less than 25%,18 and the very act of collecting gas from a landfill quickly dehydrates a covered site in a few years because half of the gas removed (by weight) is water vapor.

In addition, the liquids need to be evenly distributed. Unfortunately, moisture is not dispersed throughout landfills. Municipal solid waste is exceedingly heterogeneous, heavily compacted in a landfill to about eight times its original volume, interspersed over each day's lift with daily cover, and often confined in splayed open plastic bags, all of which creates highly preferential paths of flow. Earlier estimates from the 1990s are that liquids only reach 23% to 34% of the mass,20 and, with in-place densities more than 50% greater today, the dispersion of moisture is presumably significantly less now.

Typically, then, and at best, only limited volumes of gas is actually generated at an operating landfill, before it is closed tight. Even for that short period, decomposition is essentially restricted to isolated pockets where there are aggregations of food scraps and grass clippings that transport their own moisture with them, as well as at the bottom where hydraulic heads accumulate above clogged leachate lines and gravel beds. Differences in cover and operational practices implicate whether there is any replenishment or supplementation of moisture levels in situ that, in some cases, increases gas generation. After closure, and for as long as the cover seal maintains its integrity, gas generation rapidly tapers off as the site, for a time, takes on the intended characteristics of a "dry tomb." After the cover eventually fails, gas generation resumes until the residual carbon is exhausted and the site is biologically stabilized.

None of this wide moisture related variation in the rate of decomposition, and gas generation, is accounted for by FOD modeling, which represents a continuous function and that divergence underlies the irrational outputs the model generates.

Anomalous outputs. The extreme inexplicable and anomalous variability of the results the FOD model produces, which is widely reported in the literature, undermines its credibility at the outset. Even the EPA AP-42 background paper acknowledged that in its analysis:

"The recommended defaults k and Lo for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH4 emissions that ranged from ~30 to 400% of measured values and had a relative standard deviation of 0.73."

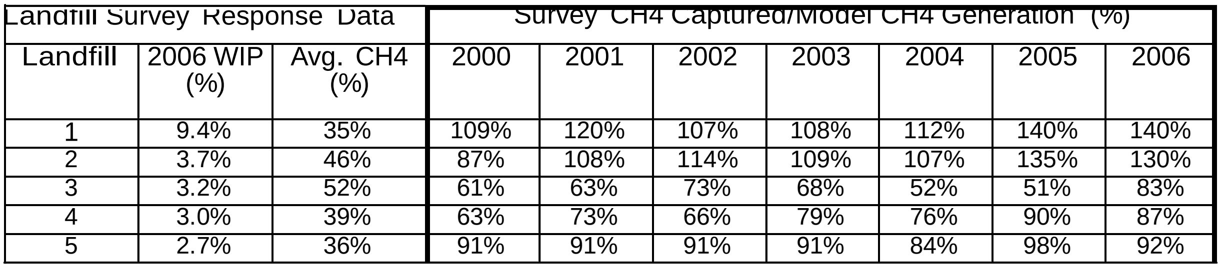
The most recent survey by Thompson of the results of FOD modeling in landfills concluded that:

"Landfill gas models continue to receive criticism due to their poor accuracy and insufficient validation: most model results have not been evaluated against methane recovery data. A few studies have compared methane recovery data to estimates of methane generation from models, but only for a few landfills. This limited approach is inadequate to validate the model for a wide, rather than site-specific application."

Similar: "Results of this study suggest that the first order model cannot always be applied to full-scale landfill gas collection data with statistical significance"

Another published paper that performed a random verification of related modeling of California landfills found a dispersion of 25 major landfills of predicted compared to actual values for gas collection efficiency, which ranged from 7% to 100%.

A more recent unpublished survey of 46 California landfills by the California Air Resources Board reproduced in Table 1 found implied gas collection efficiency from gas generation estimated with LandGEM first order equations ranging from 6% to 225% gas captured, which is an exceedingly impressive engineering feat. California Air Resources Board, Staff Spreadsheet Titled Landfill Survey Data Public (2010), released in response to a Public Records request by Californians Against Waste. Similarly, the Wisconsin Department of Natural Resources did a comparison of actual gas collected to estimate gas generation in the State's landfills and found a wide and physically impossible outputs like those found in California's study. See on-line at http://dnr.wi.gov/org/aw/wm/solid/gas/gas.htm#art6.



Landfill Survey Response Data			Survey CH4 Captured/Model CH4 Generation (%)						
Landfill	2006 WIP (%)	Avg. CH4 (%)	2000	2001	2002	2003	2004	2005	2006
1	9.4%	35%	109%	120%	107%	108%	112%	140%	140%
2	3.7%	46%	87%	108%	114%	109%	107%	135%	130%
3	3.2%	52%	61%	63%	73%	68%	52%	51%	83%
4	3.0%	39%	63%	73%	66%	79%	76%	90%	87%
5	2.7%	36%	91%	91%	91%	91%	84%	98%	92%

6	2.3%	34%	121%	121%	121%	121%	121%	121%	121%
7	2.2%	42%	99%	105%	109%	111%	105%	107%	104%
8	2.2%	14%	6%	5%	4%	6%	5%	6%	6%
9	1.9%	16%	66%	65%	65%	57%	59%	76%	76%
10	1.8%	25%	125%	113%	100%	97%	112%	124%	124%
11	1.8%	50%	64%	69%	71%	69%	66%	63%	63%
12	1.8%	42%	127%	127%	127%	127%	127%	146%	117%
13	1.4%	32%	121%	137%	128%	123%	119%	126%	126%
14	1.3%	49%	124%	119%	105%	102%	102%	76%	72%
15	1.3%	50%	59%	51%	41%	54%	54%	54%	54%
16	1.3%	43%	351%	261%	231%	226%	172%	166%	165%
17	1.2%	40%	45%	45%	45%	45%	53%	46%	44%
18	1.1%	39%	118%	118%	118%	118%	133%	118%	109%
19	1.1%	47%	78%	54%	96%	103%	90%	90%	116%
20	1.1%	44%	64%	63%	65%	40%	51%	39%	37%
21	0.8%	51%	89%	90%	103%	82%	81%	83%	108%
22	0.7%	50%	74%	73%	76%	88%	75%	94%	121%
23	0.6%	48%	152%	180%	140%	109%	104%	96%	91%
24	0.5%	48%	28%	35%	42%	50%	62%	70%	64%
25	0.4%	59%	57%	57%	57%	57%	57%	57%	57%
26	0.4%	29%	22%	22%	20%	21%	21%	25%	21%
27	0.4%	48%	23%	23%	23%	23%	15%	21%	34%
28	0.3%	38%	20%	26%	23%	21%	19%	14%	16%
29	0.3%	40%	111%	111%	116%	102%	114%	99%	98%
30	0.3%	43%	104%	104%	104%	104%	104%	93%	114%
31	0.3%	37%	29%	29%	29%	30%	33%	28%	25%
32	0.2%	42%	31%	31%	31%	31%	31%	28%	34%
33	0.2%	41%	22%	22%	19%	20%	21%	24%	30%
34	0.2%	48%	103%	85%	80%	91%	124%	123%	135%
35	0.2%	17%	6%	6%	5%	6%	6%	6%	6%
36	0.1%	48%	78%	78%	78%	102%	74%	66%	79%
37	0.1%	32%	35%	40%	38%	54%	62%	62%	50%
38	0.1%	33%	38%	17%	20%	16%	17%	27%	23%
39	0.1%	38%	257%	257%	341%	234%	234%	216%	257%
40	0.1%	37%	44%	38%	33%	18%	33%	33%	33%
41	0.0%	45%	76%	76%	76%	85%	78%	65%	76%
42	0.0%	37%	69%	66%	63%	59%	56%	52%	49%
43	0.0%	30%	46%	41%	37%	32%	27%	23%	19%
44	0.0%	27%	165%	161%	157%	138%	137%	138%	126%
45	0.0%	31%	38%	38%	38%	38%	38%	22%	47%
46	0.0%	30%	18%	17%	14%	14%	14%	14%	10%

Statistical validation failed. Initially, attempts to support the validity of FOD models was based upon a putative statistical test using regression equations of a sample that purported to show its predictions were a good fit.

The regression analysis prepared for EPA by Peer was intended to validate the FOD model's applicability to the approximately 2,000 MSW landfills in the United States, but it failed to do so. The Peer study used too small a sample of only 21 landfills, or only 1% of the population, which is too few degrees of freedom for statistical significance. Also, none of those selected for the sample were chosen randomly, which removes the normal distribution essential for regression equations to estimate a population.

Furthermore, not only was the selection process not random, it was also chosen with a specific bias that has the effect of significantly skewing results to appear to show high capture rates. This was done by limiting the sample to landfills with energy recovery. These facilities typically recirculate leachate, which accelerates decomposition and gas generation, in order to boost the profitability of electricity sales. That has been shown to increase near term gas generation very significantly, while only moderately increasing the volume of gas captured.

Since the model is blind to the fact that gas generation was augmented, the uptick in gas collected makes it seem appear that capture rates have significantly improved, even though they most probably have significantly declined.

Moreover, in addition to all those limitations, circular reasoning was used in performing the model's attempt at a statistical validation. In an attempt to assess the reasonableness of the model's estimates of Gas Generation, Eq. (3) is used to provide a putative independent estimate.

$$\left| \mathit{Gas\ captured} = \mathit{Gas\ generated} \times \mathit{Gas\ capture\ rate} \right|$$

Solving Eq. (3) for Gas Generated is shown in Eq. (4):

$$\mathit{Gas\ generated} = \frac{\mathit{Gas\ captured}}{\mathit{Gas\ capture\ rate}} \quad (4)$$

But, since only one of the two independent variables is known, this exercise rests on a house of cards. For the Gas Capture Rate is also unknown and an unsupported guesstimate is used, defeating the attempt to provide a solid foundation for the calculation. Thus, to solve the equation for Gas Generation, the study just assumed that Gas Capture Rate was 75% at all times during a landfill's life. Recalling that one of the purposes of the entire exercise was to establish a factual basis for assuming 75% capture rates in the first place, this led to a circular exercise with no statistical value. As a tautological statement, it establishes nothing about Gas Capture Rates anymore than it does about Gas Generation.

Moreover, the problem is not just that the provenance of the 75% assumption is neither an observed value nor, in view of its definition as the best systems during the limited period of their peak performance, even a reasonable assumption. In addition, in order to perform the Pearson calculations, the analysis assumed that every single landfill in the study (i) exhibited identical performance, even though operating practices significantly affecting collection efficiency vary widely among landfills, as well as (ii) achieved that same high capture rate during all phases of each sites' biologically active or latent life, including the challenging times when there is no installed or functioning gas collection system. However, US EPA has never asserted that its 75% assumption was intended to apply for each landfill at all times. Rather, to the contrary, it only purported that 75% was intended to be an average value when considered across peak times and among all landfills.

Finally, in view of the fact that moisture, which is a limiting condition for decomposition landfill decay behavior obviously reflects complex interactions, which are especially difficult to model in a heterogeneous waste mass that goes through multiple phases some of which when prerequisite moisture levels are absent. The reason given to justify the paucity of other explanatory variables in the model to explain that complex environment, such as critical internal moisture levels, is that the excluded variables had statistically insignificant estimated coefficients in earlier versions of the regressions.

But, the problem of statistically insignificant coefficient estimates arises for many reasons other than the authors' claimed lack of importance. One of the reasons for insignificant coefficients is a small sample size that leads to limited degrees of freedom, which is evident in the study. Other problems include poorly formulated equations, data measurement errors, and inappropriate error term distribution specifications and related estimation procedures. Each of these problem s exist.

This points towards an unreliable and questionable estimation process known as data mining or fishing, and not to the lack of importance of things, such as moisture, needed for a valid model. With these fishing procedures, various fuller models are formulated and discarded, not because they are not well formed or include inappropriate variables, but because the analysts did not want to confront the substantial complexities or consequences that more complete modeling would entail.

The exclusion of variables merely on the basis of low levels of estimated coefficient significance is not statistically justified, as dramatically shown by the irrational scattergun outputs it produces. For, if the excluded data are truly relevant, their exclusion leads to estimation bias and unreliable results. Coefficient significance is not an appropriate means for deleting variables from a regression model. Various appropriate tests exist for testing overall significance of a set of variables – in particular maximum likelihood ratio tests. The Peer paper does not show that these forms of significance testing were performed.

Due to all of the deficiencies discussed above, the results of the regression analyses cannot be relied upon to provide credible annual methane production quantities, anymore than the putative validation of the FOD model can corroborate that the model conforms to statistical norms. In addition to all of the problems discussed above, the low levels of R2s in the Peer study (one measure of the explanatory power of estimated regression equations) do not support a conclusion that the regression analyses provide reliable results.

The reason why the FOD model's outputs are anomalous is that its coefficients, variables and structure are incomplete and its input variables are wrong.

The most recent attempt by Thompson to validate FOD models through modifying its architecture is similarly flawed. Thompson searches for the best FOD model to validate for estimating gas generation in order to solve the mass balance equation. It uses the Pearson *correlation to compare the modeled estimates of gas generation to what it construes to be observed values among six variants of the FOD model at 35 non-randomly selected Canadian landfills with alternative assumptions about one of the factors, namely the assimilated organic fraction in the landfill, and adjustments to the values for Lo and k that are irrelevant to gas generation.*

The problems with this attempt are, first, that this so-called calibration approach is more akin to correlation fishing with a torn net. The study does not present a rational conceptual solution to errors that it identified in past modeling practices. Instead, by trial and error, it iteratively examines for each landfill the modeled gas generation estimates from each of the six variations on the same core equation, along with alternative input values, until it finds a best fitting Pearson correlations among historic landfill data.

However, the Pearson correlation does not show causality, but only a correlation that might be due to chance – a possible explanation whose probability increases markedly as the number of different values for variables and model permutations multiply, which more accurately resembles shooting fish in a barrel for correlates. In addition, the Pearson correlation is a process that says nothing about whether all critical explanatory variables, such as critical moisture levels, have been included in the model. As such, the Study's procedures are not a valid statistically appropriate procedure to derive reasonable estimates useful for future predictions of gas behavior among the population of municipal solid waste landfills.

Second, like Peer, the Thompson study is also circular. Pearson's correlation looks for linear associations between observed values and the parallel modeled estimates, here of gas generation. However, there are no observed values of gas generation to search for correlations with modeled generation outputs. In the three-term simplified mass balance equation above, only gas captured was known. In order to perform the Pearson analysis, the study resorts, at p. 2088, to the use of Eq. 4 to model further what is intended to be observed gas generation.

*But, again, this equation with three terms, which is used in an effort to provide an observed value for gas generation, also has two unknowns. To produce a value for the desired observation for gas generation, the study is forced to make another assumption, which is not based upon any observations, about the gas capture rate. In this study, collection efficiency is assumed to be the average of 75%, which is the oft-cited US EPA assumption based upon the questionable decision to focus on the best systems at the limited time of their peak performance, and 85%, which is the claimed, but disputed, Spokas assumption,*31 *or 80%. However, the EPA view is based upon a literature review that simply ignored low reported values in the published literature. As regards Spokas' claimed 85% value, as noted previously, it was even rejected by EPA and also by Thompson.*

Again, too, like Peer there is the further problem that, in order to perform the Pearson calculations, the analysis assumed that every single landfill in the study (i) exhibited identical performance during all phases of each sites' life, which is something that EPA never claimed for the assumption.

By way of comparison, incidentally, the Intergovernmental Panel on Climate Change (IPCC) states that the average lifetime capture rate equivalent to EPA's best instantaneous rate is actually as low as 20%.

Thus, when the Thompson study rejected several scenarios because they seemed to "consistently produce much higher estimates than the [observed] methane generation rates," the calculated large standard errors it thought the analysis found were actually due to its arbitrary assumption about high capture rates rather than a real statistical deviation. Had the study used the lower IPCC assumption, the findings about which model showed the best fit would probably have been reversed.

As to the intention to improve upon the Lo and k values by localizing them to the conditions in the Province in which the landfill is located, those only create the illusion, but not the substance, of refinement. Using Provincial waste audits to derive Lo is a meaningless gesture because audits are just visual inspections with very wide and unknown bands of uncertainty no better than the three-fold dispersion, from 100 to 310 m3/Mg., currently in the literature.

Similarly, the attempts to refine the k value by more closely correlating it to the Province's annual precipitation is also meaningless because the relevant criteria is moisture inside the landfills at different points in a landfill's life, not rainfall outside the facility. Directly intervening between surface and interior conditions at any given time are the permeability of any cover, any re-injection of leachate or outside liquids, in-situ compaction ratios, waste composition, the functionality of the leachate collection system, site geometry and surface grading practices. At times, in fact, after the final cover is installed and for as long as it is maintained, the waste mass will go bone dry and therefore generate very little gas (hence the moniker, "dry tomb landfills"), even if there is a monsoon raging at the surface.

But, most important for the model's structure, those factors affecting interior moisture levels vary over time. To illustrate, there is no low permeable cover until 5 to 15 years after first waste emplacement (when significant gas is generated), and then a barrier to infiltration installed and remains for as long as the cover is maintained (when very little gas is generated), after which its performance will decline and rain will re-infiltrate the site (when gas generation resumes). Therefore, the operative decay rate is not the same in those three different phases.

If the model is to reflect the critical limiting conditions for decomposition to occur, such as internal moisture levels, then the value for k also must be appropriate, and different, for those distinct time periods. That would be higher in the first and the last phase and much lower in the middle phase of a landfill's biologically active or latent life. Slightly modifying the value for k by *site location, rather than by the landfill's phase, and as a constant value under all of these conditions, fails to rectify the fundamental flaw in the first order decay model as it is presently constructed. The use of a constant k value, more closely tied to a largely irrelevant factor, fails to correct the flaws in FOD models current contemplation of k.*

Data Problems. The underlying data for the analysis is not transparent, but, we continue to believe that the data inputs used for Gas Captured and Methane Destroyed, systematically understate not only Gas Generation for the reasons described above, but also Gas Captured and destroyed.

From past experience, we believe that the aggregated data for Gas Captured continues to be grossly inflated. In the past when we last consulted for EPA, the landfill owners and vendors refused to provide actual data on gas collected at each landfill for the purpose of compiling a national data base, even though this data is typically available buried in the files of state regulators. In lieu of actual data, the nameplate capacity of the permitted flares were multiplied by the number of hours. This fails to account for subpar performance, maintenance and unexpected downtime. States should be queried to compile actual data, or if that is not possible, a statistical sample of landfills should be selected and state records reviewed to estimate the deviation from manufacturers' claimed values for the different equipment.

On a related note, while the high methane destruction values used are appropriate for flares, state enforcement officials report seeing performance for internal combustion engines below 95%. Field data should be compiled from actual state reports to improve the reliability of long-held assumptions. It is unfortunate that AP-42 continues to fail to provide any of the data that it collected in a form from which more reliable estimates might be developed.

B. First Three Phases. As noted, decomposition, and gas generation, are not a continuous function but rather are moisture dependent. In turn, the level, and distribution, of moisture depends primarily upon when the final cover is installed, and whether leachate is recirculated (and/or outside liquids added), as well as waste composition, in-situ compaction ratios, precipitation and transpiration, the presence of active gas collection wells, and surface grading.

Typically, after first waste emplacement, the gas collection system is not installed for five years in large landfills (though not in smaller ones), but it does not function to its design standards until the final cover is installed soon thereafter that creates a necessary seal for the system's vacuum forces to work properly and to prevent oxygen infiltration from the surface when it fully draws. Before the cover is installed, moisture is brought to the landfill entrained in food discards, grass clippings and left over liquids at the bottom of containers, which is supplemented by infiltrating rainfall while the top remains open while the cell fills up. Following capping, the residual moisture is quickly dehydrated by the gas systems, because half of the extracted gas by weigh is water vapor.

In wet cell landfills, discussed later, leachate is recirculated soon after first waste emplacement in order to accelerate decomposition, and often the final cover is delayed for several more years to extend the time when infiltrating rainfall can replenish moisture levels.

Thus, through the period of time that the cover is maintained, which may be approximately 30 years following closure, the landfill proceeds through three phases:

- *Pre-installation of the gas collection system*
- *Post-gas collection installation but pre-installation of the final cover*
- *Post-installation of the gas system and final cover but prior to the end of post-closure maintenance*

This is not controversial. These different phases are accepted by EPA, and, indeed, the structure is reflected in the GHG Reporting Rule, and by the landfill industry.34 These phases directly implicate how a landfill GHG inventory needs to be calculated. For, each of these phases evinces very different characteristics for the gas generation and gas collection, that varies significantly what is assumed in the First Order Decay model used in the draft inventory:

Three Phases of Landfill Life
Actual Landfill Characteristics Compared to First Order Decay Model

	Gas Generation	Gas Collection
Pre Gas Collection		
Dry Tomb	Same	Lower
Wet Cell	Higher	Lower
Post Gas/Pre Cover		
Dry Tomb	Same	Lower
Wet Cell	Higher	Lower
Post Cover-Pre Maintenance Ends	Lower	Higher

Comparing the second to the third column shows the point that Prof. Hans Oonk made to the draft version of AR4. It convinced the IPCC that the average lifetime capture rate that was equivalent to EPA's 75% assumption of what the best systems might achieve at the point of their peak performance is as low as 20%.

While the EPA and landfill industry have recognized the fact of these three phases of a landfill's life, they do not seem to appreciate the paradox that Oonk first raised, namely gas capture is only good when there is scant gas production, and when most gas is generated, there is little or no gas collection.

The draft inventory, however, recognizes neither, not the existence nor the phases or the paradox that they create. Indeed, by performing the first order decay model on total estimated landfill tonnages in each prior year, instead of on each individual landfill as a function of which phase it *is in that year, the calculation ignores all of these very significant distinctions. In aggregate, the effect, again, is to grossly understate landfill GHG emissions.*

C. Second Wave

To further complicate matters, there is a critical fourth time period in a landfill's life-cycle that is critical to include in the GHG inventory, yet is currently ignored in both the draft inventory and the GHG Reporting Rule. That is the second wave of gas generation, after postclosure maintenance ends, when the majority of a landfill's lifetime gases are generated, and, with the site abandoned, are released unabated.

Moisture restrictions. The second wave occurs because of three factors. First, as noted, the organic material in solid waste require 60% or more moisture to decompose, while incoming wastes contains less than 25% moisture. Absent additional liquids, decomposition will be minimized.

Distribution limited. Second, moisture is not evenly distributed in landfills. Solid waste is highly heterogeneous, heavily compacted to eight times its original density, inter-leafed with daily cover, and often confined in partially splayed open plastic bags, all of which combine to create highly constricted preferred paths of flow. Field studies, undertaken in the late 1990s when waste densities were only two-thirds of their current ultra-high compaction levels, show that entrained and infiltrating liquids only reach 23% to 34% of the mass.35 With in-place densities today 50% to 66% greater than when the study was done, dispersion of liquids will tend to be significantly less.

Essentially, prior to the site closing and being covered with a low permeable liner, decomposition is confined to a few areas. It only occurs where there is moisture entrained with the incoming food scraps and grass clippings and leaking out the bottom of bottles containing fluids, as well as where rain travels through cracks and fissures and then pools in pockets where food is decomposing and in voids between large particles.

After installation of the final cover, however, infiltration largely ceases and any residual moisture is quickly extracted with the gas, half of which is condensate (by weight) in the collection system, rapidly dehydrating the waste mass. From the data, probably more than half of the original carbon content in the organic discards remains upon closure.

Cover ultimately fails. Third, the final cover has a finite life. After closure, at best financial assurance regulations only provide funds for routine maintenance and for only 30 years. As EPA repeatedly stated during the 1980's leading up to the promulgation of Subtitle D in 1991, even composite liners "will ultimately fail" within decades after the agency's post-closure care requirements have expired, "and when they do, "leachate will migrate out of the facility."

the EPA recognized, the duration of a landfill's hazardous loadings that needs to be isolated may be "many thousands of years," long after the time when discharges will occur.

The early warnings from EPA were more recently reinforced from an investigation and field study conducted by the agency's Inspector General –

"EPA officials have stated that based on current data and scientific prediction, the release of contaminants may eventually occur, even with the application of best available land disposal technology. There is concern that these barriers will merely postpone the inevitable release of contaminants until after the 30-year liability has expired. As previously stated, some sites contain materials which are highly resistant to decomposition or which remain toxic forever. There have been several studies to determine the expected life span of landfill liners, and opinions on this issue vary widely. The bottom line is that not even the manufacturers claim that their liners will last forever."

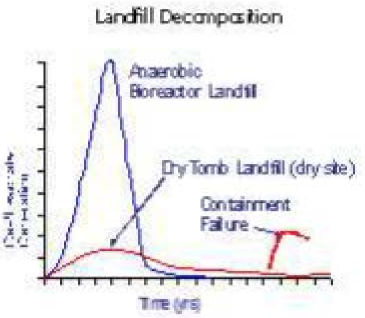
Why, then, did the EPA proceed to adopt liner-based regulations in 1991, when they were fully informed that engineered barriers will eventually fail? That question was answered by the EPA Inspector General a decade later in 2001. Extensive interviews with the agency's staff established that the reason was political, not technical–

"Landfill design requirements and post-closure maintenance for both Subtitle C and Subtitle D facilities are expected to prevent leakage in the short term; however, their long-term effectiveness in controlling releases of contaminants is unknown. EPA and others have stated that it is likely that some disposal facilities will leak at some period after they close. "However, some who commented were concerned that an extended time frame would place an economic burden on smaller businesses. Therefore, EPA officials acknowledge the lack of criteria or scientific basis for establishing the 30-year post-closure time frame. EPA made the decision to establish the time frame at 30 years, seemingly based on a compromise of these competing interests. EPA officials we spoke to agreed that the 30-year time frame was not based on specific scientific criteria or research studies."

State environmental agencies reached the same conclusion about the fact that the covers would eventually fail and lead to a second wave of gas generation after maintenance ends at closed landfills. The California Integrated Waste Management Board stated:

"However, the initial term of 30 years for P[ost] C[losure] M[aintenance] is unlikely to resolve all the environmental issues related to a closed landfill in California. Since Subtitle D was promulgated, research shows that certain wastes in some landfills stabilize in a short period of time and that,at those landfills, the potential to impact the environment may only last for a short portion of the conventional 30-year PCM period. On the other hand, some landfills may remain a threat to the environment for longer than 30 years. For example, stakeholders have reported to Board staff that landfill gas control systems have had to be installed at landfills that had not operated for up to 60 years. Dry tomb landfills (favored by Subtitle D and 27CCR) indefinitely

suspend and/or retard the decomposition process such that a breach in containment (e.g. extreme climate or earthquake event or inappropriate land use, or simply failure of equipment or containment barriers) could trigger uncontrolled production and release of landfill gas and leachate, and public contact with waste. The state of the science thus indicates that municipal solid waste landfills will in many cases pose a significant threat to the environment well beyond the conventional 30-year PCM period." (See accompanying FIGURE showing a second wave of gas generation denoted as "containment failure.")



Similarly, Washington state's Department of Ecology has stated:

"The extent to which today's landfills adequately protect human health and the environment is a subject of debate, however. Requirements that govern siting, operation, closure, and post-closure are stringent and extensive. While the newest landfills are state-of-the-art facilities, they are far from benign in their impacts. Landfills may still affect the air, land, and water but to a significantly lesser degree than before today's standards went into effect. As waste decomposes in landfills, methane and other hazardous gases are generated. Methane is a greenhouse gas concern because its impact is twenty-three times that of carbon dioxide (EIA). Leachate from decomposing matter in landfills can contain hazardous constituents. If landfill liners and/or leachate collections systems fail, then groundwater and surface-water pollution can occur. No liners are engineered to be 100 percent impenetrable or to last forever without some sort of failure. In fact, US EPA officials have stated that problems can occur more than thirty years after closure of a landfill, pointing out that 'even the best liner and leachate collection system will ultimately fail due to natural deterioration.'"

In addition, the Wisconsin Department of Natural Resources has also pointed to the same inherent flaw in dry tomb designs for landfills:

"The problem with dry tomb landfills is that the organic wastes in them remain largely undecomposed. They represent a continuing and large potential source of methane gas, as well as a potential source of groundwater pollutants. The essentially perpetual management of these problems represents a long-term financial liability to the waste management industry, and potentially to the state, if public monies have to be used to clean up future problems."

Furthermore, in the last three years, many in the landfill industry have conceded these basic facts, as well. The Executive Director of the Solid Waste Association of North America (SWANA), John Skinner previously headed EPA's Office of Solid Waste where he had a major role in drafting Subtitle D. Dr. Skinner has recently written:

"The problem with the dry-tomb approach to landfill design is that it leaves the waste in an active state for a very long period of time. If in the future there is a breach in the cap or a break in the liner and liquids enter the landfill, degradation would start and leachate and gas would be generated. Therefore, dry-tomb landfills need to be monitored and maintained for very long periods of time (some say perpetually), and someone needs to be responsible for stepping in and taking corrective action when a problem is detected. The federal Subtitle D rules require only 30 years of post-closure monitoring by the landfill operator, however, and do not require the operator to set aside funds for future corrective action. Given the many difficulties of ensuring and funding perpetual care by the landfill operator, the responsibility of responding to long-term problems at dry-tomb landfills will fall on future generations, and the funding requirements could quite likely fall on state and local governments."

Dr. Skinner's predecessor at SWANA, Lanier Hickmanexpressed the same view more forcefully:

"Currently many policymakers view F[inancial] A[ssurance] for landfills from the perspective, 'If it ain't broke, don't fix it.' However, the question is not 'if' there will be future landfill problems, but 'when.' Since FA requirements are the last line of defense before the public winds up with the costs for corrective action, it is critical that an FA mechanism be able to guarantee coverage of expected landfill costs."

Or from Peter While, an environmental scientist with Procter & Gamble – "...The dry containment method of operating a landfill has been described as long-term storage of waste rather than waste treatment or waste disposal, and does have some significant drawbacks. There will always be pockets of moisture within waste, and it is generally accepted that all lining and capping systems will eventually leak so rain and/or groundwater will eventually enter the site. Thus, the decomposition of the organic fraction of the waste will eventually occur, with resulting emissions of landfill gas and leachate. Since pipes and pumps buried within the waste eventually clog up and fail, there will be less chance of collecting and treating these emissions if they occur in the distant future."

Or from John Pacey, one of the premier landfill engineers –

"The containment provided by these landfills offers environmental protection initially; however, at some point beyond the 30-year [postclosure] period, there may be partial failure(s) of the containment lining system (underlying and overlying the waste). The primary environmental issue associated with partial containment system failure and moisture infiltration is the potential associated increase in gas and leachate production and the resulting impact of uncontrolled leachate and/or landfill gas releases to the environment. The nature and magnitude of the

releases exiting the landfill and their resulting impacts are directly related to the amounts of organic waste not yet decomposed."

Thus, a very substantial fraction and quite possibly a significant majority of the carbon in the incoming wastes remains when the landfill is closed due to insufficient and unevenly distributed moisture while open. Also, eventually the cover will fail after maintenance ends, reigniting a second wave of gas generation that will probably be larger than the first wave. At that time, there will be no gas collection and all of the future gases from the residual decomposables will escape into the atmosphere.

Not only is it vital that the fifth phase of a landfill's life be acknowledged, but also it is necessary to include the future emissions that will flow from today's discards in the annual GHG inventories. Yet, for the organic discards buried in the year for which the inventory is prepared, EPA's current practice purports to track each landfill's actual performance only in that annum.

However, in fact, we understand that the agency does not even recognize the fact that a not insignificant fraction of the gases generated that year are from open or not fully closed cells

where there is either no gas collection or no low permeable cover. In those cells, the Gas Capture Rate is zero or a fraction of collection system's peak performance, while EPA's calculations presumes capture rates are a constant and optimal at all times, belying any claim that it is tracking each landfill's behavior in that year.

Even if the new four-phase protocols included in Table HH-3 of the GHG Mandatory Reporting Rule were followed in the inventory – which we do not believe it was – that would still ignore the fifth phase when, most likely, a majority of the gases are generated and, since none of those are captured, most of the fugitive emissions occur.

Accounting for future emissions. EPA has previously defended the inventory's omission of the vast majority of postponed GHGs that arising from the residual carbon in the wastes buried today. It has argued that the inventory only encompasses emissions estimated to occur in that year.

However, this view produces a result that ignores the majority of the delayed emissions associated with wastes deposited in that year, which, under EPA's protocols will never be counted for in the relevant future. This result is akin to assessing a person's dose absorption of a

24-hour time release pill in the first hour after its being swallowed, and ignoring the further uptake in the following 23 hours.

Moreover, EPA's opinion is fundamentally inconsistent with the IPCC principles that the agency has itself restated in its reports:

"CH4 emissions from landfills are counted [under the IPCC guidance in inventories of anthropogenic GHG emissions.] Even though the source of carbon is primarily biogenic, CH4 would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH4 formation. Note that this approach does not distinguish between the timing of CO2 emissions, provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO2, it does not matter whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor)." Finally, the refusal to acknowledge the future stream of methane emissions that inevitably will follow from the burial of organic discards today is also in fundamental conflict with other practices used elsewhere in the inventory. In order to compute the equivalent warming effects of other greenhouse gases to CO2, each of which has different residence times, the accepted convention uses an assumed common 100-year period for the time each gas, released today, will remain in the atmosphere before it decays or is absorbed. Since methane actually only remains in the atmosphere for 12 of those 100 years, its actual impacts are diluted by being spread over 88 years when it is no longer present.

In the event EPA's decision is to bar recognition for those delayed impacts, then, to be consistent, the protocols also must use a single-year basis for calculating the different gases' warming potential, something that would increase methane's carbon-equivalence by more than 100 times. But, the protocols cannot responsibly use a century long frame of reference in one chapter and an instantaneous snapshot in another and produce a coherent analysis in the conclusion.

As to the complaint that there is no nomenclature to properly account for the future stream of emissions in the inventory for the current year, there is a well-trod analogous mechanism to do this. Accounting routinely incorporates into the present a future stream of income flows that derive from an investment made today to best pick from various options. This directly resembles continuing gas emissions from decaying wastes discarded in that year. That technique is the net present value analysis, long used in economic planning and decision-making.

As to the complaint that present value type of calculations require making projections about future events that are not precisely known, that, too, is a red herring. For one thing, the current present-only analysis is already replete with made up assumptions without any factual basis, such as the gas capture rate. For another, ignoring future consequences that will follow from today's actions does not eliminate uncertainty. To the contrary, ignoring the future is a palpable decision that there will be no future decomposition activity from today's discards, which is a totally absurd result. Tomorrow's uncertainty cannot be eliminate by pretending it does not exist.

Of note, a present-value type of calculation attributing future emissions from wastes buried today to the current year is a practice that the IPCC has used elsewhere. The estimation *technique of compressing into the present the future emissions from today's sources has more recently been specified as the appropriate methodology in the IPCC's Clean Development Mechanism program.*

E. Oxidation

The draft inventory continues the practice of continuing to assume that 10% of escaping methane is oxidized in the cover soil. Previously, EPA has effectively rested its case on the Czepiel study, which found in field and laboratory studies during 1994 that 10% of the methane generated in a landfill, was oxidized in the cover soil over the course of a year.

When the gases that are emitted are diffused throughout the overlying soil blanket, as would have been the case with most landfills constructed before 1991, this study would be applicable. However, modern landfills gases are not diffused at the surface throughout that earthen layer, because, since 1991 a composite cap has been required under that soil blanket, including in practice a 60-mil (or 1 / ") high density polyethylene plastic membrane that effectively impedes the passage of gases from the waste into that cover soil.

This is key. It means that instead of the methane diffusing throughout the topsoil for maximum oxidizing effect, the gases that are released above the landfill are concentrated in high fluxes at a handful of cracks and tears in the plastic sheet. Concentrated high flux emissions quickly overwhelm the capacity of the topsoil to oxidize the escaping methane through these hot spots.

Czepiel expressly stated that not only was his study not done at a landfill with a synthetic geomembrane, but also, "[p]eriodic maintenance of the cover materials has minimized significant surface cracks" in the clay layer, as well. That is to say, nothing in his study can be used to describe what happens to the methane that flashes through a small number of hot spots on the top face of the landfill.

He further reemphasized again in his conclusion that his findings did not apply when gases are released in high fluxes through narrow cracks:

"Waste settlement, surface erosion and soil dessication often promote significant surface cracking, providing paths of minimal resistance to gas flow, effectively bypassing microbial influence. Our study generally lacked surface cracks, although his characteristic may not be representative of the entire spectrum of landfill surfaces."

Furthermore, a consultant for the U.K. Department on the Environmental conducted a comprehensive study involving 250 measurements at a landfill with a composite cover and found that there was no oxidation effect:

"Methane oxidation is only observed where the diffusion gradient through the cap is very small, and therefore the methane oxidizing bacteria can cope with the rate of supply of gas. When higher fluxes predominate there is little evidence either for or against methane oxidation being a significant component of emission control."A similar field examination by researchers at a Swedish landfill corroborated the U.K. findings.

Other Technical Constraints on Oxidation

Even if, for the sake of argument, methane oxidation were able to occur landfills with plastic liners, there are many other limitations of Czepiel's findings when attempting to apply them without limitation to the typical landfill and across time.

For one thing, in northern climates, oxidation is improbable during cold winters. Also, in addition to the small cracks in the geomembrane, similar problems can afflict the clay liner as well. In the northern climatic zones, the freeze/thaw cycle is a constant source of cracking, and in hot,arid climates, clay is susceptible to cracking from dessication.

For another, remembering that landfill gas is heavier than air and seeks the path of least resistence, no one has yet been able to satisfactorily determine what proportion of landfill gases escape through the top of the landfill–where any oxidation that occurs would take place – and, through the bottom and even the sides of the site or through the leachate collection system – where it would not, as EPA has previously pointed out. Then, too, there is the practical complications of maintaining optimized laboratory conditions for methanotrophs to oxidize methane over the long term at a real site.

In any case, even if for the sake of argument it were considered appropriate to give the benefit of oxidation for the period of time prior to the installation of the final cover when there emissions might diffuse through any soil layer, EPA itself has stated that a concomitant reduction in collection efficiency would have to be registered to account for the lack of a seal necessary for efficient gas collection.

For the foregoing reasons, it is no longer rational or responsible to continue conducting the waste section of the GHG inventory exactly as it has done so in the past only because it has always done it this way, regardless of the fact that its foundations have been vitiated by the EPA's reports.

With kinetics experts as part of a team, we stand ready to accept a commission to revise the present first order decay model to properly reflect the things that we know make its present formulation useless.

Commenter: American Gas Association (AGA)

Comment: *The Draft Inventory indicates that overall lifecycle emissions for the natural gas value chain are low, and they are getting lower. While the new EPA methodology significantly increased the estimated emissions from production, the rest of the natural gas lifecycle experienced large reductions in emissions per unit of gas consumed. Natural gas processing experienced a 15% decline, transmission and storage experienced a 26% decline, and distribution experienced a 27% decline. These emission reductions from processing, transmission and distribution more than offset the increase that EPA estimates in the Draft Inventory for natural gas production. Even accepting EPA's inflated estimate of emissions from production, the natural gas lifecycle has experienced an overall reduction in emissions per unit of gas consumed.*

Commenter: American Gas Association (AGA)

Comment: *We do have significant concerns about EPA's methodology for estimating production emissions. The methods used to derive the emissions factors and population counts for well completions that do or do not capture methane using reduced emissions completions (RECs) are seriously inaccurate and are at odds with the EPA's goals and proud history of data-driven policy and regulation. The EPA's strong reputation means that this anomaly has been given undue credibility in the public debate over shale gas production and the lifecycle carbon footprint of natural gas. According to the analysis performed by URS Corporation for America's Natural Gas Alliance (ANGA), it appears EPA has estimated that only 15% of the hydraulically fractured well completions in 2010 used REC technology to capture methane in the flow back phase. EPA assumes that the other 85% of hydraulically fractured well completions in 2010 must have released substantial amounts of methane to atmosphere or flared it and emitted carbon dioxide (CO2). In contrast, ANGA submitted the results of a survey in January 2012 showing that eight major shale gas producers completed almost 1500 hydraulically fractured wells in 2011, and 93% of these were green completed. Only 7% were vented or flared.*

Commenter: American Gas Association (AGA)

Comment: *In comments on the Draft Inventory, El Paso Corporation also submitted extensive data based on actual field measurements using methods dictated by EPA's GHG reporting rule at natural gas transmission compressor stations, LNG terminals and storage facilities. This data indicates that the Draft Inventory has also over-estimated the amount of GHG emissions from other sectors of the natural gas value chain. In light of ANGA's and El Paso's data, we urge EPA either to update the emissions estimates for natural gas cleanups, unconventional well completions and workovers and other sources to reflect the actual data that has been submitted in comments, or to exclude them from this year's Inventory until more robust data and* *methodologies have been developed. At a minimum, we strongly urge EPA to include a statement at the beginning of Chapter 3 of the Final Inventory, and in a footnote to every table and figure that includes natural gas emissions indicating that the EPA has received data relating to the natural gas emissions estimates that indicates that the methodology should be revised, the Agency is reviewing and revising its methodology, and that, until this process has been completed and EPA has developed an appropriate methodology based on robust data, that the emissions estimates for natural gas production should not be relied upon for analysis or regulatory action.*

Commenter: American Gas Association (AGA)

Comment: *In September 2012, producers will also submit reports under the mandatory GHG reporting rule, 40 C.F.R. Part 98, Subpart W, that will provide the number of hydraulically fractured shale gas well completions in 2011 that are either green completed, vented or flared. AGA urges EPA to incorporate this new Subpart W data on 2011 well completions and other Subpart W sources when EPA drafts the next Inventory for the period 1991-2011. The new Subpart W data will be reported by Sept. 28, 2012. This will allow plenty of time for EPA to include the new data before issuing a new draft Inventory of 2011 emissions in January 2013.*

Commenter: Pioneer Natural Resources

Comment: *Specifically, in the 2011 draft inventory, EPA made limited, specific changes to the Natural Gas Systems Section 3.6 that dramatically increased emissions from field production 9 times between the 2010 and 2011 Draft Inventory and more than doubled the previous estimate for all natural gas system emissions. Pioneer's comments below focus on two of these major alterations: a revised methodology for calculating emissions from natural gas well cleanups (also called liquids unloading) and a new category of gas well completions and gas well workovers (re-completions) with hydraulic fracturing. EPA's 2010 Inventory estimated 2008 methane emissions from natural gas field production at 14.1Tg C02 Eq. In the 2011Draft Inventory, estimated methane emissions in 2008 were 122.9 Tg C02 Eq (revised to 118.6 Tg C02 Eq during the QA/QC process for the 2012 Draft Inventory), a 9 fold increase. No other emission source underwent such a striking adjustment. These changes remain in this 2012 draft inventory and Pioneer would like to take this opportunity to outline discrepancies and omissions in the data and analysis, and offer accurate in-house numbers as a comparison tool for EPA to use in revising their inventory.*

EPA must develop accurate, peer-reviewed emissions and activity estimations that are based on valid data, assumptions and calculations. Transparency in data sources is critical for industry, regulators, as well as the public nationwide who all have a vested interest in these published

GHG emissions estimates. Accuracy in this inventory is of the utmost importance as state and federal regulators will inevitably rely in some aspect on this data for future regulatory initiatives. In light of serious concerns with respect to the methodology and the quality of the data generated for the Draft Inventory, Pioneer mirror's ANGA's request and asks that EPA either update the emissions estimates for natural gas cleanups and unconventional well completions and workovers or exclude them from the inventory until more robust data and methodologies have been developed and subjected to public review and comment. At a minimum, EPA should include a statement at the beginning of Chapter 3 of the Inventory, and in a footnote to every table and figure that includes emissions from Natural Gas Systems, indicating that it has received information and data related to Natural Gas System emissions estimates that indicates that the methodology needs to be revised (as EPA itself has pointed out in the text), that the Agency is in the process of revising its methodology, and that until such time as the methodology has been revised an implemented, and new emission estimates based on the revised methodology are available, the emissions estimate sin the inventory should not be relied upon or otherwise used as the basis for any analysis or regulatory action.

Commenter: Pioneer Natural Resources

Comment: *Additionally, Pioneer, as well as ANGA and other trade associations, commented on EPA's proposed Oil and Gas Sector New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants proposed rule in November 2011 in regard to EPA's unconventional well completions and workover data, pointing out the flawed activity and emission factors and offering realistic estimates. However, despite these and previous requests for correction, faulty estimates and methodologies remain the same in this Draft Inventory as in EPA's 2011 Draft Inventory. EPA seems to recognize that their methane emissions estimates do not accurately reflect emissions from the industry and point out this fact, however further steps must be taken to publicize the unreliability of this data.*

Commenter: Pioneer Natural Resources

Comment: *In the QA/QC and Verification Discussion, Recalculations Discussion, and Planned Improvements discussions of Section 3.6 in the 2012 Draft Inventory, EPA states*

The natural gas inventory is continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practice. EPA has received information and data related to the emissions estimates through the inventory preparation process and the formal public notice and comment process of the proposed oil and gas New Source Performance Standards {NSPS} for VOCs. EPA plans to carefully evaluate this and all other relevant information provided to us. Subsequently, all relevant updates will then be *incorporated, as applicable, in the next cycle of the Inventory. In light of this current review of information and data, for the 1990-2010 Inventory, emissions for the natural gas sector were calculated using the same methodologies, emission factors and sources of activity data, as the 1990-2009 Inventory. Additionally, EPA has held the 2010 estimate for emissions from hydraulically fractured wells constant at 2009 levels (ie: maintained the same activity data and voluntary reductions for hydraulically fractured gas well completions and existing hydraulically fractured gas wells). For the production sector, EPA intends to evaluate additional data on emissions reductions, particularly those related to gas well cleanups and regulatory reductions from well completions and if appropriate, will incorporate revisions into future inventories. Additionally, accounting for the uncertainty of emissions reductions to more accurately provide upper and lower bounds within the 95% confidence interval, will be investigated. EPA also intends to investigate improvements to its estimates of emissions from hydraulic fracturing, including revisiting the estimates for workover frequency.*

Regardless of EPA's recognition of the receipt of data based on actual operations form natural gas operators and adequate time to assess this data, they have failed to modify their estimates and have included the same overstated, fundamentally flawed data in the text, tables, and annex of the Draft Inventory as if it were accurate information that should be accepted as true and correct. TO further compound Pioneer's concern, this data will inevitably be relied upon by regulators for future rulemaking. Pioneer requests that the operational data that was submitted in the NSPS comments be considered by EPA as well as the Pioneer-specific information provided below in these comments. Further, Pioneer is concerned that EPA's release of this emissions data does not meet the Information Quality Act requirement that information disseminated by EPA be accurate, complete, reliable and unbiased.

Commenter: Pioneer Natural Resources

Comment: *The change in the methodology for estimating emissions from natural gas well liquids unloading (referred to by EPA as cleanups) account for the majority of the increase in emissions from natural gas production from the 2010 Draft Inventory to the 2011 and 2012 Draft Inventories. First, in the Methodology section of 3.6, EPA states that the emissions factors do not take into account the use of technologies that reduce emissions. To take into account the use of such technologies, data is collected on regulatory and voluntary reductions, according to EPA. The revised methodology contains a critical flaw in its failure to include emissions reductions from the use of artificial lift systems, such as plunger lifts, among others, that are not reported under the Natural Gas STAR Program. It is not sufficient that EPA utilized results from the Natural Gas STAR Program to account for these technologies since not all Natural Gas STAR partners report all emission reduction activities. In fact, artificial lift is underreported even among Natural Gas STAR partners as it is often regarded as an economic recovery technology as opposed to an emissions reduction technology. The omission of emissions reductions from the* *application of these technologies results in a worst-case scenario approach that is not appropriate for an emissions inventory, and dramatically overestimates the emissions from natural gas production.*

Commenter: Pioneer Natural Resources

Comment: *Further, EPA appears to have developed their methodology for calculating emissions from liquid unloading events based on two sources. The first source, an EPA/Natural Gas STAR report "Lessons Learned: Installing Plunger Lift Systems in Natural Gas Wells" provides an equation for estimating the volume of gas vented during a blowdown. EPA states that it used production and permit data obtained from HDPI in October 2009 for at least part of the data to run the equation. HOPI supplied information of well depth, shut-in pressure, well counts and well production data. However more detail on the data actually used, particularly the data used to calculate shut-in pressure (which is needed to ensure that EPA focused on low pressure wells where liquid unloading is more prevalent), is necessary to adequately evaluate the methodology and results. The equation only provides the volume vented fore each blowdown. To complete the inventory, EPA needs to know how many wells required cleanups and how many blowdowns are required annually at those wells. The documentation for the inventory does not indicate what data were used to estimate these two variables. EPA must provide greater transparency in the data upon which they base their calculations. While the HPDI data would have provided the total number of wells, it is unlikely that HPDI's production data would have provided information of which wells perform cleanups and number of blowdowns performed each year at those wells. EPA has estimated these two variables - Appendix B of the TSD developed in support of Subpart W of the GHGMRR uses data from a 1992 survey conducted by GRI to estimate that 41.3% of conventional wells require cleanups. Pioneer believes that hits figure is dramatically overstated. The 1992 survey was of 25 well sites. To determine the average number of blowdowns at each well, the TSD uses a simple average of 31 blowdowns per well based on publicly available data from two Natural Gas Star partners. These estimates are based on outdated well estimates and two isolated data points to determine the average annual number of blowdowns at each well. EPA's lack of adequate data sets and transparency is concerning and these emissions estimates that EPA has assumed based on this extremely limited data set are not reasonable and should not be relied upon. EPA should work further with industry to acquire more accurate activity and emission factors to run their calculations and estimate emissions. Based on Pioneer's actual operational experience for company gas wells in 2010, less than 1% were blown down to the atmosphere during liquid unloading operations.*

Pioneer mirrors ANGA's request and ask that the emissions should be estimated per event using approaches similar to the EPA MRR Subpart W and then apply the emissions estimates to wells that 1) use cleanups and 2) do NOT use an emission reduction technology of any kind. Then the emissions should be adjusted for reasonable estimates on the amount of gas that is flared v.

vented. In general, Pioneer feels that the methodologies between the Draft Inventory and Subpart W should be concurrent for consistency in calculating, reporting, and disseminating information

Commenter: Pioneer Natural Resources

Comment: *In the 2011 GHG Inventory, EPA added two new categories: unconventional gas well completions and unconventional gas well workovers.10 The addition of these two categories accounted for 28 percent of the increase in estimated 2008 emissions from natural gas field production from the 2010 to the 2011 GHG inventory. The TSD prepared in support of Subpart W outlines the approach EPA used to develop the emission factor. The TSD uses only four data points to develop an estimate of emissions from completions. EPA took these four estimates and calculated an emissions estimate of 9,175 Mcf/completion for unconventional wells. EPA applied the same number to workovers (and recompletions as EPA uses these terms interchangeably).*

Not only is the emission factor based on only 4 data points, but none of the data points were purported to be representative estimates of emissions from completions or recompletions. Rather they are case studies from a voluntary EPA program aimed at reducing emissions and, as such, they are reporting the results of a handful of projects in the field. They are not based on standardized and audited protocols and were into intended to be the basis of inventory-grade information disseminated by EPA. Moreover, case studies, by their nature, are typically based on projects that will provide statistically significant results and are not based not he average project. So, it follows that since notable projects are the ones that capture the greatest amount of emissions, using these captured emissions to estimate average uncontrolled emissions will lead to grossly inaccurate results.

Commenter: Pioneer Natural Resources

Comment: *In regard to the activity factors used by EPA for completion and recompletion estimates, in the Annex EPA states that, 10% of the total fractured gas well count is the number of gas well workovers with hydraulic fracturing in a given year. In addition, EPA states that due to the lack of publicly available data, 51% of hydraulically fractured gas well completion and workover emissions are assumed to be flared across the 1990-2010 time series, even though it is likely that some fraction of these required reductions are recovered for sale. EPA assumes this estimate because of regulations in some states, such as Wyoming, require completion emissions to be controlled and not vented and therefore, emissions in these states must be either recovered or flared. Pioneer believes that this assumption is not valid. Again, Pioneer urges EPA to work with industry for a realistic representation of the industry operational practices and when capturing gas with Reduced Emissions Completions (REC) is performed. For example, in 2010,* *Pioneer operated approximately 4600 natural gas wells, of which over 98% were stimulated through hydraulic fracturing. Of these hydraulically fractured wells Pioneer refractured less than one-percent. This percentage varies significantly from EPA's ten-percent refrac figure. Further, in regard to RECs, currently Pioneer performs green completions at all Barnett Shale wells and flares instead of venting as in the company's South Texas and Eagle Ford operations when gathering lines are not available.*

Commenter: TJ Blasing, ORNL

Comment: *Appendix, Table A-35, Electric Power Coal sems to nose dive from 25.96 in 1990 to values around 17 between 1995-2010.*

Commenter: Linda Heath

Comment: *Forest carbon stocks dropped 15% but carbon sequestration estimates relatively unchanged. In Table 7-8, in comparison to last year, the total live tree biomass carbon (above and below), using the year 2010 as an example, was 84.7 percent of what it was last year, dropping from 20,552 TgC to 17,417 TgC, a loss of 3,135 TgC or 11,495 TgCO2e. This relative difference as well as magnitude is pretty much the same throughout the period.*

Page 7-21, lines 5-10 says that a new method was used to calculate this pool, and that the carbon stocks in this pool is lower, but that the relative effect on the net annual stock change was minimal. Indeed, using the year 2009 as an example, in comparison to last year the change in net annual stock change was 0.9% greater sequestration, which is 5 Tg CO2e or .36 TgC for that year. This is well within the range of uncertainty. Does the given explanation mean that if the change in sequestration had not been minimal that the new set of equations would not have been adopted? What is the scientific basis for choosing to switch to the new set of equations?

Commenter: Linda Heath

Comment: *New forest biomass equations are from gray literature but urban forest tree biomass equations remain unchanged. The reason for asking is because the biomass equations used for many years now were published in Forest Science, the premier peer-reviewed scientific journal of the Society of American Foresters. (The EPA inventory urban tree estimates also are said to be based on equations similar to these.) The forest biomass equations used in these new estimates were published in a gray literature proceedings paper. The original methodology was* *updated in a compilation of all the necessary volume equations needed to calculate biomass estimates for all trees of the US, recently released as a Forest Service General Technical Report. It is unclear how gray literature-based equations are more accurate and more scientific than peer-reviewed scientific literature. Further, this newer set of biomass equations appears to not be based on any new field-collected tree-biomass data.*

Commenter: Linda Heath

Comment: *Individual-tree error reduced? In what way? Line 21, page 7-21 of the GHG inventory draft says that this approach appears to reduce the level of individual-tree error. However, it is not totally clear what evidence this statement is based on. For example, in this new set of equations, based on the description of this approach, it sounds as though trees growing on one side of, say the Indiana-Ohio state border, will have a certain biomass estimate, and the same size and species tree on the other side of the border will have a different biomass estimate, simply because the different FIA units are using different volume equations. How does having two estimates for the same tree in the same database contribute to a reduction in uncertainty at the individual tree level, or even the perception of a reduction of uncertainty?*

Commenter: Linda Heath

Comment: *Plot level updated estimates are based on what? The Forest Service apparently only recently initiated a coordinated study to collect new biomass field data for biomass model development, and when that study is*

completed the equations will presumably change again. It is not clear in this US EPA GHG Inventory chapter or cited literature what the scientific reason is for adopting an interim set of equations. For some of the states in the early years of these inventories there is only plot-level data anyway, and conversion estimators for those always have to be revised for this analysis in order to calculate the change between inventories. In what document is it shown that this new group of estimators is better than the previous group of estimators for plot-level change?

Commenter: Linda Heath

Comment: *What message does this send to other countries about how to conduct forest carbon estimation? Because there is so little change in the GHG inventory estimates due to these equations, one would think the real story must be about estimating carbon stocks. If CO2 was worth $5 per ton, in terms of the difference since last year's estimate in terms of money in hand would be $25million, but in terms of stocks, $57.475 billion dollars disappeared since last year.*

How does this change in carbon stocks compare to the stated uncertainties? What would experts from other countries think of such a notable change? What is the scientific basis for the change to these equations, given that other pools remain to be updated too?

Commenter: Linda Heath

Comment: *A commentary on continuous improvement as the reason. Although not noted in this text, an explanation of this drop in carbon stocks is explained in not a research article, but a commentary in the March issue of the Journal of Forestry, the journal for the Society of American Foresters, a professional society. It came out very late in March. The explanation given there is that this is a result in the pursuit of scientific rigor to do better. If scientific rigor was used in this updating, then where is the peer-reviewed, thorough analysis on which the new biomass equations is proven scientifically more accurate than the last set? What are the accuracy and/or precision improvements from these changes? Why update the standing dead tree when the down dead wood in the same pool is not being updated this year but will be updated soon, which will again change the dead wood pool? IPCC discusses accuracy, comprehensiveness, consistency, transparency, etc. It is unclear how continual improvement relates to these characteristics. Including new recently collected data that has undergone a quality assurance process into the system is one thing. Continually fiddling with methodology of the system is another.*

Commenter: Linda Heath

Comment: *Update some pools and not others which may have been calibrated based on the old biomass estimates? That new standing dead tree data was added is a laudable goal, although the biomass equations are untested. But the dead wood pool contains both the standing dead trees and down dead wood, and the down dead wood is still modeled even though the data has existed for years. Why update the dead wood pool now, only to have to update it again with the new data in the next year? It is unclear how the soils information is calibrated. One would think it would be more defensible in a policy relevant framework to focus on a thoroughly peer reviewed system for all the pools, publish in peer-reviewed journals, and then change the estimates one time.*

Commenter: Linda Heath

Comment: *In summary, the scientific basis for making the change is not well-stated. It is necessary and an important goal to ensure the estimates are based on the best scientifically-based methodologies, which are implemented correctly as needed for the GHG inventories, and* *so it is expected that the approach and results will indeed change over time. My comments are not to question whether the best intentions went into these estimates. I am sure all parties involved have the best of intentions. Rather, my comment is that the scientific basis for making this change at this time is not well stated and does not appear to be well-supported in the GHG inventory text. Other countries could now constantly change their forest GHG inventories, following the US lead. Having to make continual improvements is not always an indication of sound scientific advancements, just as adopting a process of continual improvements is not automatically evidence of a sound scientific process. If someone was auditing the estimates of countries to ensure that cheating in reporting was not occurring, just what would they think of this? What would people think of the national GHG inventory reporting system if all countries, Annex I and non Annex I, constantly changed their estimates in a manner similar to this? Please consider providing a clear reasoning for adopting this approach at this time, especially in light of the notable drop in carbon stocks.*

Commenter: Robert J. Kopka

Comment: *I believe a summary of total global emissions of the various greenhouse gases could be useful, especially as the climate changes of GHG sources shift to another part of the world. These global emissions should be further divided as natural sources or those directly induced by humans on a world wide basis to better document what is being emitted world wide and how the United States might influence worldwide emissions. Some examples of natural sources that should be tracked over time as the world warms are the release of methane from the ocean sediments and permafrost, and the release of carbon dioxide from the soil. The location of sources of man-induced GHG (by country) may change over time as well. Future policies that may be enacted in the United States, may influence GHG emissions from another country or vise cersa. The change in the location should be documented over time in this and future reports, so we can be aware of how U.S. policies may influence global GHG emissions.*

Commenter: Robert J. Kopka

Comment: *I also believe that the amount of carbon dioxide released during the production of solar panels should be a separate line iten in many of the GHG source tables. The production of solar panels may become asignificant source of GHG emissions, if solar becomes a major future energy source because the production of these panels requires the use of a great quantity of energy.*

Commenter: Department of Transportation

Comment: *Transportation estimates in Tables such as 2-15 and 3-12 could include tailpipe biofuel combustion estimates as an italicized item similar to the wood biomass and ethanol consumption estimate currently presented in Tables ES-2 and 3-1. It would also be worthwhile to include a footnote explaining why these emissions are not included in the total, and point to the Renewable Fuel Standard literature for details on upstream analysis of transportation fuels.*

Commenter: Department of Transportation

Comment: *DOT recommends that EPA include italicized biofuel consumption estimates in Tables A-1 and A-2 of the Annex. This could eliminate the need for a separate Table A-3.*

Commenter: Department of Transportation

Comment: *The increased biofuel consumption (and the related accounting issues) could also be discussed in the transportation narratives of Sections 2.1 and 3.1, which could also point to the RFS literature for details on upstream analysis of transportation fuels.*

Commenter: Department of Transportation

Comment: *p. 12, lines 32-33: Should acknowledge the increase in fuel prices, including the spike from 2006-2008 and increases since prices bottomed in late 2008 / early 2009.*

Commenter: Department of Transportation

Comment: *p. 14, Table 1-12: the Residual Fuel Oil footnote refers to FHWA definitions of vehicle classification. We believe that this footnote is misplaced or an additional footnote was intended for Ships and Other Boats.*

Commenter: Department of Transportation

Comment: *Ship/boat residual fuel energy consumption and CO2 emissions have some odd fluctuations---particularly between 2009 and 2010—that do not appear to be consistent with current EIA fuel oil & kerosene sales data, either adjusted or unadjusted. DOT staff are not* *aware of any substantive reason to believe domestic or international shipping fuel consumption increased substantially in 2010.*

The inventory report shows a 64-percent increase domestic shipping fuel consumption (and hence CO2 emissions), from 205 TBtu in 2009 (Table A-12) to 337 TBtu in 2010 (Table A-11). Summing domestic + international bunkers, the inventory shows an increase of 18-percent, from (205 + 605 = 810 Tbtu) to (337 + 620 = 957 TBtu) in 2010 (Table A-11, A-12, and A-33). The Energy Chapter Table 1-12 provides summary information.

*The EIA's adjusted fuel oil and kerosene sales show vessel bunkering of 5.46 billion gallons (821 TBtu, assuming 6.317 *10^6 Btu/bbl) in 2009, rising to 5.93 billion gallons (891 TBtu), an increase of only 8 percent. The unadjusted EIA fuel and kerosene sales data shows a 7.5-percent decline between 2009 and 2010. The EIA data should be the source of (or at least consistent with) the sum of domestic + international bunkers.*

http://www.eia.gov/dnav/pet/pet_cons_821rsda_dcu_nus_a.htm

We would recommend re-checking the source data and its conversion into energy units.

Comments Received during the Public Review Period on the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012

Commenter: Giles Ragsdale

AECOM

Comment: Regarding chapter ES.2. – My opinion is that under this recent trends paragraph, note should be taken of the results of Figure ES-15. There is a positive story to tell in that despite increased population and Real GDP, emissions per capita and per $GDP have been trending downward since 1990 and by more than a negligible amount.

Comment: Regarding figure ES-3: I think the title should be revised. I might be confused, but I do not think the data on the graph reflect the title of the figure. I see that each year's annual total compared to 1990 is represented, but I do not see the "Cumulative Change" noted in the title. For cumulative change, it would seem that 1991 would be -25 as noted, but 1992 would be 52, 1993 would be 261, etc.

Commenter: William Herz

National Lime Association

Comment: In response to the last iteration of EPA's Greenhouse Gas Inventory Draft, published in March of 2013, NLA submitted comments that recommended EPA discontinue using the IPCC emission factors to account for LKD emissions, and that the agency also take into account CO2 emissions from off-spec lime, scrubber sludge, and other wastes. A copy of NLA previous comments is included in Attachment 1. This issue continues to be important to NLA members, not only to help ensure the completeness and accuracy of the data EPA publishes but also to ensuring the achievement of EPA's stated goal of agreement and alignment with the GHG mandatory reporting system.

Currently, EPA calcination emission calculations rely solely on output-based emission factors from the IPCC 2006 GHG Guidelines, which we believe are outdated. Central to the NLA's previous comments were recommendations to adopt accurate calcination emissions calculation methodology for:

- Lime Products; and
- Lime Kiln Dust (LKD); and
- Off-spec lime, scrubber sludge and other wastes.

Each of our recommendations was based on analysis of actual production data, including CaO and MgO oxide contents of lime and LKD, which had been provided to NLA by member companies. These results of this data were incorporated in the comments NLA submitted to your office last year. The comments, together with the data we provided, should be sufficient to provide EPA with the basis to generate more accurate emissions estimates for LKD and other lime products (including off-spec lime and scrubber sludge).

In sum, NLA's earlier comments concluded that while the IPCC's output-based approach for estimating calcination emissions from U.S. lime products may be accurate as to the overall data to be published, it nonetheless understates emissions from LKD and other byproducts and wastes generated in the United States. For that reason, NLA recommended that lime calcination emissions be multiplied by a factor of 1.06 (not 1.02) to account for LKD and a factor of 1.02 to account for wastes generated at lime plants; neither of these are currently accounted for which we believe is a critical error.

When the current Draft Inventory of U.S. Greenhouse Gases and Sinks 1990-2012 was published on February 21, 2014, it was disappointing that none of our recommendations concerning the use of more accurate correction factors had been adopted and EPA continued to rely on the outdated IPCC factor of 1.02 to account for LKD. Likewise, EPA took no action in relation to off-spec lime and other wastes.

As we stressed in our previous comments concerning the earlier draft, NLA conclusions and recommendations were premised on our belief in the need for EPA's published data to be accurate; especially when NLA's members are willing to supplement the agency's data with accurate data of their own. Because EPA relies solely on the questionable IPCC LKD generation rates, calcination emissions continue to be understated. Accordingly, we again urge EPA to adopt our recommendations; if there are other supporting data we can also provide that would add further weight to and/or support for our recommendations, please let us know.

In addition, we recognize that EPA has a substantive interest in having both the GHG Inventory and the Mandatory GHG Reporting system be in agreement as much as possible. This is important not only for EPA's credibility but also for the public's and stakeholders' understanding of these issues. In this regard, as we stated in our previous comments:

Lime Kiln Dust

"...based on data reported to NLA from our members, emissions from generating LKD account for about 6% of calcination-related emissions from lime manufacturing (in 2011, it was 5.8%). Currently the IPCC multiplies lime product-related emissions by a "correction factor" of 1.02 to account for LKD. The IPCC Guidelines acknowledge that this correction factor for LKD is borrowed from its chapter on cement, which in turn explains that the factor for cement kiln dust (CKD) is relatively low because most CKD is recycled back into the process.

By contrast, the lime industry does not recycle LKD back into the process, and thus borrowing such a factor to account for LKD-related calcination emissions is inappropriate.

EPA's reliance on the IPCC's LKD generation rate of 2% (rather than 6%) understates calcination emissions from our members alone by 535,610 tons. This is roughly 5.4% of our members' total emissions, and twenty times the understated calcination emissions described earlier for lime products."

<u>Off-Spec Lime, Scrubber Sludge, and Other Wastes</u>

"The IPCC Guidelines do not to take into account calcination emissions resulting from wastes commonly generated at lime plants (e.g. off-spec lime that is not recycled, scrubber sludge). Again, based on 2011 data reported to NLA from our members, calcination emissions from production of such wastes account for approximately 1.7% of total calcination emissions, or 256,000 tons. To address this omission, we recommend that EPA multiply quicklime calcination emissions by a factor of 1.02."

Conclusion:

NLA believes the deficiencies in the proposed inventory are significant and should be corrected. In the aggregate, EPA has underestimated lime emissions by approximately 814,000 CO2 tons; as the off-spec materials generate 256,000 tons (completely unaccounted for in the inventory) and 535K tons (the difference in LKD emissions when utilizing the correct emissions factor; (854K – 319K)). This represents an underestimate of approximately 5.1%, which is not insignificant.

Commenter: Marlen Eve

USDA Animal and Plant Health Inspection Service

Comment: Executive Summary:

Page 1 lines 29-30: Excellent!

Page 2 lines 9-10: Needed for effective comparison.

Page 5 Figure ES-3: Very impressive and encouraging trend!

Page 10 lines 10-14: This is excellent – it enables an accurate sectorial picture otherwise difficult to estimate.

Page 14 lines 27-31: Noteworthy point that technology improvements can be so effective in this area.

Page 15 lines 9-10: Good to see this point made in Summary – an area USDA is researching and still in need of improvement.

Page 16 lines 19-21: Suggests an area in need of more oversight and regulation in a fast growing industry.

Page 17 line 13: Noteworthy effect of improved land-use and forests as sink. Question – why have these sinks not increased since 2007 – compared to notable improving trend over 1998-2004?

Page 20 lines 7-10: Good point to note – not sure this is widely recognized – and how difficult it is to manage for lower levels. This is a clearly-needed USDA research area.

Page 20 lines 29-30: Good to mention in Executive Summary given this is a problematic area in many developing counties including China and India.

Page 27 lines 7-9: Good point to make – it identified an area that could benefit from future research.

Page 5 line 27: Is this very long table needed in Executive Summary?

Page 11 line 15: Reference that low fuel prices during period 1990-2012 in part contributed to increase in number of vehicle miles. Hopefully this can be substantiated through economic comparison – I think fuel prices increased considerably during this period relative to other consumer prices. And when I look at some internet sites such as: http://www.inflationdata.com/inflation/images/charts/Oil/Gasoline_inflation_chart.htm, they seem to reflect that the statement that gas cost has remained low and thus the conclusion that this leads to increase in number of vehicle miles could be challenged.

Page 17 lines 17-18: Is this very long table needed in Executive Summary?

Comment: Introduction:

Page 13 line 1: Very good summary of all input sources of data and expertise in one diagram!

Comment: Agriculture:

Page 1 lines 5-8: Very good way to focus on what is critical in agriculture practices!!

Page 1 lines 16-20: We liked this up-front summary and focus on what is critical!

All pages: There is a great abundance of numbers, informational statements, tables and some figures. The details can be overwhelming but we view the text and supporting data as essential, comprehensive, well-balanced, and superbly organized by easy to read, consistent sections on each source of non-CO2 GHG. The methods used should be of value to other countries as a ‘role model’ on what data is needed and on how to assess uncertainty and apply verifications and recalculations.

Overall—comprehensive and well-written chapter on a difficult subject.

Several locations in the Chapter: There are references to number of cattle/dairy cattle increasing/decreasing but overall CH4 emission increasing due to digestibility. I can look at some trends in the NASS that would indicate that the trends in numbers of cattle stated don’t quite coincide with my quick review of NASS. But they do state a lot of adjustments that they made to the numbers that I don’t have the time to work through. And I definitely don’t have the background on digestibility – few, if any, in Veterinary Services would. So I can’t validate or refute, and would not want our brief review to be considered a “peer review”. I would hope that this section and others in the paper have been appropriately peer reviewed to avoid any improper conclusions developed which could have an undue negative influence on animal agriculture.

Comment: Land Use, Land-Use Change, and Forestry:

All pages: As commented on Agriculture Chapter we note that there is a great abundance of numbers, informational statements, tables and some figures. The details can be overwhelming but we view the text and supporting data as essential, comprehensive, well-balanced, and superbly organized by easy to read, consistent sections on each source of GHG. The methods used should be of value to other countries as a ‘role model’ on what data is needed and on how to assess uncertainty and apply verifications and recalculations.

Overall: Comprehensive and well-written chapter on a difficult subject. This category is especially important to developing countries where land use is in flux and where practices such as forest cutting and clearing, fire use, and extensive degradation by grazing is wide-spread.

Comment: Recalculations:

Page 1 lines 2-4: We felt this is one of the most important chapters in the Report given it provides a protocol and verification annually of the estimates. It has the salutary benefit of credibility of estimated made given they are constantly under re-evaluation as new data (past and present) and methods are developed and accessed. Some of the changes appear large in magnitude – but this may not be unusual where only imprecise data was available initially.

Possibly add a summary or a tabulation of what this report achieved in the way of new data, new methods and new findings that were not mainstream in prior analyses and thinking.

We note with interest some prior assumptions (or simple lack of information or awareness) on aspects of agriculture and land use / forestry of special interest. Some of these new perceptions are now and in the immediate future will be important in on-going and future negotiations over land and land practice monitoring by different countries.

Commenter: Marlen Eve

USDA Agriculture Research Service

Comment: Agriculture chapter: Page1 line 6:

Seems to imply C removal is only related to land-use change. Assuming other management does not have an impact?

Comment: Agriculture chapter: Page 1 line 18:

"other cropping practices" a little vague – such as?

Comment: Agriculture chapter: Page 2 lines 16-17:

"These non-ruminants emit significantly less CH4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH4 is lower."

Add … lower than in a rumen.

Comment: Agriculture chapter: Page 9 line 20:

"…increasing use of liquid manure management systems, which have higher potential CH4 emissions than dry systems." Are there any estimates on the adoption of methane capture from liquid manure?

Comment: Agriculture chapter: Page 29 line 3-4:

This sentence needs to be rewritten without all the "nots:"

"However, renewal of pasture that is **not** rotated with annual crops occasionally is **not** common in the United States, and is **not** estimated."

Comment: Agriculture chapter: Page 30:

In general DAYCENT appears to perform well, but recent work by Campbell et al., 2014 suggestion DAYCENT may underestimate N2O emissions. "Overall, DAYCENT performed well at simulating stover yields and low N2O emission rates, reasonably well when simulating the effects of management practices on average grain yields and SOC change, and poorly when estimating high N2O emissions. These biases should be considered when DAYCENT is used as a decision support tool for recommending sustainable corn stover removal practices to advance bioenergy industry based on corn stover feedstock material." (Campbell et al., 2014). Thus, as more empirical data becomes available it could be used to improve DAYCENT.

Comment: Agriculture chapter: Page 41 Table 6-27:

Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues: Is it correct that this is refers only to residue that are burned in the field or does it include residues harvested and burned for energy – clarify.

Commenter: Other

USDA

Comment: Page 6-7, line 18: "months" should be inserted after "4-6."

Commenter: Carrie Reese

Pioneer

Comment: Gas Well Completions/Workovers with Hydraulic Fracturing:

Pioneer commends EPA's consideration of stakeholder comments to the 2013 Inventory and subsequent development of control technology-specific, net emission factors for gas well completions and workovers with hydraulic fracturing. This approach makes use of a more comprehensive data set and provides greater transparency regarding EPA's accounting of emissions reductions carried out by the industry. However, Pioneer feels that this methodology can still be improved upon.

Emissions quantified in the Greenhouse Gas Reporting Program (GHGRP) for 2011 and 2012 are based on engineering estimates and best available monitoring methods (BAMM) in addition to direct measurements. In Pioneer's initial review of 2011 and 2012 GHGRP data for "HF completions that vent", average emissions per event (Mg CH4) computed by an estimation methodology appear to be nearly tenfold that of directly-measured emissions. Until there is further understanding of the nature of these events, Pioneer suggests that EPA develop control technology-specific, net emissions factors focusing on measured data from the GHGRP and measured data contributed by other accepted sources.

Published by the University of Texas at Austin in September 2013, Measurements of Methane Emissions at Natural Gas Production Sites1 (Allen, et. al) quantifies emissions from 27 gas well completions in multiple production regions. Representative gas well completions from nine operators, which conduct about half of all new well completions, were sampled. The measurement results, a product of peer-reviewed, scientifically-robust, and fully-disclosed methodology, present a basis to consider the reasonableness of other data provided under less controlled circumstances.

Referred to in the 2014 Inventory, the November 8, 2012 document entitled "Inventory of U.S. Greenhouse Gas Emissions and Sinks: Updating Emissions Estimate for Hydraulically Fractured Gas Well Completions and Workovers", identifies four categories of events and proposes new emission factors for each of these categories. The following table provides a comparison of the EPA emission factors in the 2014 Inventory to the measurements reported by Allen, et al. {2013). The study reports emissions data for completion flowbacks only, with no measurements for workovers with hydraulic fracturing.

Type of completion flowback or workover	*EPA Emission Factor*	*Observed Emission Factor from Allen, et al., (2013)*
Wells that vent without flaring or Reduced Emission Equipment (REC)	41	0.83 (observed mean) 0.8-124 (range)*
Wells that flare (without REC)	5	Not observed
Wells with REC that do not flare	3	4
Wells with REC that flare	6	1.5-18

*The wells that vented without flaring or REC observed by Allen, et al. (2013) had much lower potential emissions (0.83 Mg) than the average potential emissions for all of the observed wells (124 Mg). If the wells in this category observed by Allen, et al. are representative of national populations of this category of wells, then the emission factor for this category would be 0.8 Mg per event; in contrast, if the sample of all wells observed by Allen, et al. (2013) is considered representative of this category and it is assumed that the deployment of REC equipment is random among all of these wells, then the emission factor for this category would be 124 Mg per event.

Comment: Liquid Unloadings:

In previous comments to the 2013 Inventory, Pioneer expressed support for EPA's development of net emissions factors for liquid unloading events, but also noted concern that Subpart W calculation methodology may tend to overstate emissions. Pioneer requests that EPA continue to consider improvements to the calculations in this emissions category.
In the study referenced above, Allen, et al. (2013) also reported on emissions from liquid unloadings.

The sample set of nine manual unloadings proved insufficient to allow for extrapolation at a national scale, and the study team is conducting additional measurements to supplement the data collected in the first part of the study. However, Allen, et al. (2013) does report an important observation from the initial effort, demonstrating that the Subpart W methodology for liquid unloadings without plunger lifts (based on engineering calculations and not direct measurements) overestimates emissions for every measured event. Collectively, emissions are estimated five times higher than the measured emissions.

Pioneer again suggests that underlying causes for overestimation of emissions may be EPA's assumption that a full wellbore volume of gas is vented with each unloading and the assumption that a well unloads for one hour on average. In addition, Allen, et al. (2013) observed intermittent flow rates during unloading events and proposes that EPA's assumption of a continuous gas flow rate may be another contributor to overestimation .

Comment: Pioneer applauds EPA's commitment to refine emission estimates in the U.S. Greenhouse Gas Inventory to reflect the best available information. As the body of scientific and engineering knowledge continues to grow with regards to emissions from oil and gas activities, Pioneer contends that emphasis must be placed on directly-measured data and that results from these direct measurements should in turn inform corresponding estimation methodologies . Collaboration is the key to this process, and Pioneer looks forward to continued dialogue with EPA.

Commenter: Chris Busch

Energy Innovation: Policy and Technology

Comment: The EPA should take steps to address clear evidence that its inventory of GHG emissions is undercounting methane. In the short run, as part of finalizing the 2014 inventory, the agency should make the case for a significant effort to improve the inventory of emissions from the natural gas sector. In the longer run, the agency should develop a plan for integrating top-down data as well as new technologies that operate at ground level that can assist in leak detection and measurement. The federal government should be placing more emphasis and devoting more resources to this effort.

Comment: Brandt et al.'s work illustrates the value of top-down measurements to provide evidence of overall emission levels over large areas. The EPA should move to collect airborne measurements into its GHG inventories. By conducting measurement campaigns, EPA will be able to obtain atmospheric data that is more comprehensive across space and time. This will enable the agency to identify aggregate emissions levels with much greater accuracy and will help to improve confidence intervals. Current confidence intervals are much too small.

Comment: Emerging technologies can link emissions back to sources, enabling the EPA to conduct an effective ground-level measurement campaign. Infrared cameras are effective at locating leaks, and their use has been required under a recently approved Colorado regulation. Low cost stationary detectors are also under development. The newest detectors can locate leaks and estimate their magnitude from a distance, which reduces the challenge of acquiring property owner permission that bedevils direct on-site measurement.

Comment: The current oil and gas boom has been unleashed by a wave of technological innovation (directional drilling, hydraulic fracturing, and other emerging techniques, like "acidizing"). Governments need to keep pace with faster innovation on the regulatory side. New monitoring technologies are an opportunity for greater accuracy, and the EPA should move quickly to use these technologies to transform government monitoring of emissions. Better monitoring of emissions will help the EPA solve the mystery of the missing methane and provide the best objective guidance to policymakers, regulators, and society.

Commenter: Kerry Kelly

Waste Management

Comment: WM is pleased to see that the emissions from the waste sector and landfills in particular, continue to trend downward, while methane emissions control via gas collection and combustion in renewable energy projects or flares continues to grow. We also noted with interest, the discussion of planned improvements to measuring landfill emissions by replacing the default 10 percent oxidation with a more accurate, science-based estimate. It is this aspect of the Draft Inventory that is the subject of our comments.

The Agency refers to a growing body of peer-reviewed literature describing both field and laboratory studies that all indicate that the default oxidation value of ten percent understates the oxidation rates achieved at well-managed landfills. EPA's careful analysis of peer-reviewed literature and field measurement studies resulted in recent regulatory changes to estimating methane oxidation in landfill cover in the Greenhouse Gas Mandatory Reporting Rule (GHG MRR). These changes allow greater use of site-specific conditions rather than national default assumptions and will greatly increase the accuracy of landfill facility methane emissions estimation. We urge that the Agency also update its national inventory methods to reflect these changes, so that it can improve the accuracy and reliability of the U.S. GHG Inventory.

Comment: The EPA's Decision to Revise the Methane Oxidation Factor Used in the GHG MRR is Well Supported by Peer-Reviewed Science:

Numerous studies have been conducted worldwide and referenced in the scientific literature that address and document methane oxidation in cover soils, as well as gas collection efficiency. In 2009, The Journal of Environmental Quality published a comprehensive literature review. The paper references over 60 technical documents dating from 1960 to the present, with the majority of the papers being published in the 1990s and 2000s. Overall, based on review of 42 determinations of the fraction of methane oxidized in a variety of soil types and landfill covers, the mean fraction of methane oxidized across all studies was 36 percent with a standard error of 6 percent. For a subset of 15 studies conducted over an annual cycle, the fraction of methane oxidized ranged from 11 percent to 89 percent with a mean value of 35 percent + 6 percent, nearly identical to the overall mean.

In July 2007, the Solid Waste Industry for Climate Solutions (SWICS) released its first white paper titled Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills (White Paper). The public and private members of SWICS shared the White Paper with EPA as it developed the

GHG MRR requirements for evaluating and reporting MSW landfill emissions. In January 2009, SWICS updated the White Paper to incorporate additional studies noted above.

Since the release of the 2009 White Paper, a number of studies have been published in peer-reviewed literature, most notably an entire special issue of the journal Waste Management (2011) on Landfill Gas Emission and Mitigation sponsored by Consortium for Landfill Emissions Abatement Research (CLEAR). CLEAR is an International Waste Working Group (IWWG) Task Group, which focuses on landfill gas emission to the atmosphere. The group has members from 12 countries, across four continents. A number of papers in the special issue focus on the use of compost biocovers, bio-windows or permeable gas dispersion layers to treat and oxidize landfill gas in situ (Huber-Humer et al., 2011; Pedersen et al., 2011; Scheutz et al., 2011; Pawlowska et al., 2011; Dever et al., 2011; and Jung et al., 2011). Additionally, several papers in the special issue, Ranchor et al., (2011); Abichou et al., (2011) and Chanton et al., (2011b), examined the response of the methane oxidizing microbial community to methane loading to the cover soil. Two key papers, Bogner et al., (2011), and Spokas et al., (2011), describe recent work in California where field measurements of emission and oxidation were coupled with extensive modeling efforts. Chanton et al., (2011a) published the results of 37 seasonal sampling events at 20 landfills with intermediate covers over a four-year period. Abichou et al. (2011b) examined the best approach towards describing central tendencies in oxidation data and reported that the results were generally distributed normally so that mean values could be used.

In November 2012 SWICS, with the participation of Dr. Jeffrey Chanton of Florida State University and Dr. Morton Barlaz of North Carolina State University, finalized an addendum (2012 Addendum) to the Methane Oxidation section of the 2009 White Paper. The 2012 Addendum includes methane oxidation results from evaluations of 90 landfills as compared to the 47 published evaluations available in 2009.

In reviewing and incorporating the results of these peer-reviewed studies of landfill methane oxidation, the 2012 Addendum updated the 2009 White Paper results as follows:

1. Clay cover: The number of studies in clay cover increased from five in 2009 to 31 in 2012. The mean fraction of methane oxidized increased from 18 percent to 30 percent, while the median fraction oxidized increased from 14 to 29 percent.

2. Sandy soils cover: The number of studies in sandy soils doubled from eight to 16, with the mean oxidation value changing very little (55 to 54 percent) while the median value increased from 43 to 50 percent methane oxidized.

3. “Other” covers: The number of studies in “other” cover soils increased by nine and both the mean and the median fraction oxidized values increased slightly.

4. The overall mean oxidation value across all of the studies increased from 35 to 38 percent while the overall median oxidation fraction increased from 31 to 33 percent.

Comment: The SWICS 2012 Addendum Definitively Supports a Significant Increase to the Current Default Value of Ten Percent:

The 2012 Addendum concluded that the EPA default oxidation value of 10 percent underestimates typical methane oxidation and is not representative of expected methane oxidation at sites utilizing organic, clay, sand or other cover types. EPA derived the default value from one field study performed at one poorly maintained landfill with no gas collection system, Czepiel et al. Analysis of the 90 studies highlighted in the 2012 Addendum indicates that if a single value is considered for methane oxidation it should be between 33 and 38 percent.

The 2012 Addendum also examined methane oxidation as a function of methane loading to the cover layer of the landfill. Recent studies show that the percent oxidation is an inverse function of the rate of emission (Stern et al., 2007; Rachor et al., 2011; Chanton et al., 2011a,b). At lower emission rates, the methanotrophs in the soil cover can consume a larger portion of the methane delivered to them, potentially oxidizing 95 to 100 percent (Humer and Lechner, 1999, 2001a, Huber-Humer 2008; Powelson et al., 2006, 2007; Kjeldsen et al., 1997). As flux rates increase, the percent oxidation decreases and the methanotrophs can become overwhelmed with methane. Thus, as methane emission increases, percent oxidation decreases (Powelson et al., 2006, 2007).

A mathematical model of cover oxidation developed by Dr. Tarek Abichou of Florida State University (Abichou et al., 2010), demonstrates that at lower methane fluxes, oxidation rates are equal to the methane loading to the soil cover. Oxidation keeps pace with flux, and the soil cover is able to oxidize all of the methane coming from below. At lower loading rates, methane oxidation is equal to 100 percent. As flux increases, the cover is not able to oxidize all of the incoming methane, and the percent oxidation falls off. Therefore, percent oxidation starts to decrease as the methane loading to the cover increases. This relationship is shown clearly in the laboratory column studies of Rachor et al., (2011). Field studies have also confirmed this relationship between methane flux and percent oxidation (Chanton et al., 2011a, b). At low rates of methane emission, the percent oxidation is near 100 percent. As emission rates increase, the percent oxidation decreases. This analysis served to support the approach that EPA finalized for determining a more accurate methane oxidation fraction by calculating the methane flux rate for the landfill.

In addition to the 2012 Addendum, the landfill sector provided data for 262 private and public landfills reporting under Subpart HH. The dataset allowed the Agency to evaluate several possible options for determining more accurate methane oxidation fractions. The data conclusively showed that the average oxidation fractions for different soil cover types are all well above the default 10 percent value required by Subpart HH, and underpin the need for a revised default value or more refined method for determining an oxidation fraction at a site.

Comment: WM recommends that the Agency carefully consider its analysis underpinning its decision to estimate facility-level methane oxidation by calculating the methane flux rate and consider how that methodology could be used at the national inventory level. The work done by the Agency in updating methods for facility-level calculation of methane oxidation will greatly improve the accuracy and reliability of emissions estimates for landfills. We urge EPA to endeavor to make similar improvements to its national inventory of emissions and sinks at landfills.

Commenters: Anna Moritz, Kevin Bundy, Sparsh Khandeshi,
Center for Biological Diversity and Environmental Integrity Project

Comment: We are concerned that the emissions factors and global warming potential for methane that are currently employed by EPA have resulted in a significant underestimate of U.S. anthropogenic methane emissions. First, multiple studies have reported far higher leakage factors from oil and natural gas operations than EPA currently uses. It is essential that EPA arrive at accurate numbers. In addition, even reported leakage numbers necessarily underestimate emissions because they omit undiscovered and unreported leaks, such as those by smaller operators. EPA should immediately commence on-the-ground data collection and, until the results from these efforts are available, account for these factors by presenting a range of likely underreporting. Second, the climate impact of methane is underestimated because the inventory reports normalized methane emissions using solely a 100-year global warming potential (“GWP”) and an outdated value for the GWP.

Methane is an important component of climate strategies to avoid Arctic disaster and other catastrophic tipping points. Unlike other traditional greenhouse gases that have atmospheric lifetimes of a century or more, methane remains in the atmosphere for only about 12 years. This means that a reduction in emissions today will not only slow the increase in radiative forcing, but also result in actual decreases in radiative forcing in a short time – just over a decade. When we are considering how to address the collapse of the Arctic cyrosphere or avoid near-term tipping points, methane and other short-lived climate pollutants present an opportunity for rapid reductions in climate forcing.

Because methane mitigation is an important climate strategy, it is essential that the current emissions levels from US sources be accurately characterized. This includes both emissions factors for various industries and quantification using the most current values for global warming potential: a 100-year GWP of 34 and a 20-year GWP of 86.

Comment: Emissions factors from oil and gas operations should be revised:

There is compelling evidence that leakage rates from oil and gas operations are far higher than EPA emission factors suggest. For instance, Miller and colleagues recently used atmospheric measurements to estimate that actual methane emissions are about 1.5 times larger than EPA estimates, with fossil fuel methane emissions more than two times higher than estimated. Observations from oil and gas operations in Colorado indicate that inventories underestimate methane emissions by at least a factor of two. Leakage rates over a Utah gas field were recently estimated at 6.2 to 11.7%, well above the rates assumed by national inventories.

Moreover, EPA's data for oil and combined oil/gas wells omit the impact of hydraulic fracturing. A recent white paper from Environmental Defense Fund summarizes findings from a number of studies to conclude that emissions factors used in EPA's current inventory underestimate methane emissions from oil wells that employ hydraulic fracturing.

Another major source of methane emissions from the oil and gas sector is leaks from pneumatic devices. A recent study calculated emission factors for pneumatic devices to find that national emissions from this source are likely at least twice the amount predicted using the emission factors in the US GHG Inventory. This is another area where improvement of emission factors is essential.

We urge EPA to consider the range of data available and update the emission factors that are used in the GHG inventory to accurately reflect methane emissions from both venting and leakage in the oil and gas industry. These data are critical as industry leaders and decision makers consider mitigation options.

Recent reports have also substantiated an alarming rate of leaks from decaying gas pipeline systems across the country, creating the need for systematic, on-the-ground data collection to obtain an accurate quantification of emissions from this source. For example, according to a recent study, the two distributors of natural gas in New York City and Westchester County reported 9,906 leaks in their combined system for 2012 alone, and gas distributors nationwide reported an average of 12 leaks per 100 miles of the 1.2 million miles of gas main pipes across the country. More than 5,800 leaks were detected from aging gas pipelines underneath the streets of Washington, D.C. These samples indicate that EPA's data are incomplete, and we urge EPA to note this fact and undertake the efforts necessary to provide an accurate accounting next year.

Comment: The GHG Inventory should quantify methane emissions using AR5 GWPs:

EPA recently finalized technical amendments to the Greenhouse Gas Reporting Rule. These changes included updating the methane GWP from the values in the IPCC Second Assessment Report to those in the Fourth Assessment Report ("AR4") for reporting in year 2015 and beyond. While this was an important improvement, we and other organizations joined Clean Air Task Force in recommending that EPA utilize the most up-to-date science and adopt the most recent methane GWPs from the IPCC Fifth Assessment Report ("AR5") as well as require reporting of both 100-year and 20-year methane GWPs.10 EPA declined to adopt the most recent estimates of methane's GWP because current international reporting requirements under the United Nations Framework Convention on Climate Change employ only 100-year GWPs and will begin using AR4 GWPs in 2015.11

While we understand EPA's need to comply with international reporting requirements, we renew our call upon EPA to consider updating the emissions reported in the U.S. GHG Inventory to reflect the AR5 GWPs, as well as report normalized emissions using both 20-year and 100-year GWPs for methane. The US GHG Inventory is important domestically for both government and private-sector decision-making and analysis. This is a purpose separate from international commitments and requires more precise quantification of climate impacts. We appreciate the inclusion of Appendix 6.1 in the draft GHG Inventory, which provides emissions estimates as calculated with both AR4 and AR5 100-year GWPs. We ask that EPA make this information more prominent so that users will be more likely to find and employ the updated emissions estimates. Furthermore, it is important that EPA use the most accurate GWP for methane, which includes carbon cycle feedbacks.

We further request that EPA consider reporting emissions using both the 100-year and 20-year GWP for methane as this will allow the full consideration of climate consequences. The 100-year GWP gives a better sense of how reductions can influence long-term climate stabilization, while the 20-year GWP is useful when considering tipping points and near-term climate impacts. Furthermore, the AR5 values for GWP have changed substantially since AR4. The AR5 methane GWP of 34 is significantly higher than AR4 – 36 percent higher. The AR5 20- year GWP is 86 (19% higher than the AR4 GWP). These substantial increases in GWP mean that emissions data reported using AR4 GWPs or earlier are understated. Accordingly, EPA must revise the GWPs used in the inventory and ensure that they properly reflect carbon cycle feedbacks.

Comment: EPA Must Clarify Data Sources and Emissions from Biomass Electricity Generation:

According to the Draft Inventory, CO_2 emissions from woody biomass and woody biomass consumption (measured in trillion Btus) in the electricity generation sector increased nearly tenfold between 2011 and 2012. It is not clear, however, how these emissions estimates were derived. Although emissions of biogenic CO_2 associated with electricity generation are reported primarily for informational purposes pursuant to international accounting conventions, accurate emissions data are critical to evaluating domestic renewable energy programs and accounting for the actual climate consequences of increasing biomass energy generation.

The Draft Inventory states that biogenic CO_2 emissions from the electricity generation sector data were calculated using EPA's Clean Air Market Acid Rain Program dataset, while emissions from other sectors were obtained from EIA's Monthly Energy Review.[13] An annex to the Draft Inventory explains that "there were significant differences between wood biomass consumption in the electric power sector between the EPA (2013) and EIA (2013) datasets." Accordingly, "the electricity generation sector's woody biomass consumption was adjusted downward to match the value obtained from the bottom-up analysis based on EPA's Acid Rain Program dataset."

The increase in emissions between 2011 and 2012, if accurate, represents a dramatic expansion of emissions from this industry—nearly a full order of magnitude over the course of only one year. It is impossible to discern, however, whether the Draft Inventory's emissions estimates are either comprehensive or consistent.

The EIA Monthly Energy Review data used for other biomass emissions estimates does not show a similar increase in woody biomass consumption between 2011 and 2012; in fact, these data show a slight decline in both wood and other biomass "waste" consumption. The increase thus must be reflected, if anywhere, in EPA's Clean Air Market dataset. Again, however, this is impossible to discern because the full dataset does not appear to have been included or explained further in either the Draft Inventory or the annexes.

Indeed, it appears that the AMPD dataset may be under inclusive of electrical generation facilities using woody biomass as fuel. For example, a query performed on the AMPD website for 2012 emissions data from all programs and all facilities returned 4,828 records nationwide, only 23 of which list "wood" as the primary fuel source; CO_2 emissions from these facilities in 2012, where emissions were reported at all, totaled only about 2.7 million metric tons. There are, of course, more than 23 wood-burning power plants operating in the United States; indeed, there are more than 23 such facilities in California alone, although no California plants appear in the query report generated by the AMPD dataset.[18] Of course, if there are numerous biomass power plants that are not listed in the AMPD dataset, use of this dataset for a "bottom up" emissions estimate will likely underestimate emissions from this sector.

Given these apparent inconsistencies, EPA should clarify what data set it is using to estimate biogenic CO_2 emissions from electricity generation and should ensure that these data are inclusive and comprehensive enough to produce an informative report.

Comment: Conclusion:

In sum, we commend EPA for compiling and reporting extensive data from various sources of greenhouse gases within the United States. There remain, however, some areas where improvements are needed to maximize the utility of the GHG Inventory for both international reporting and informed domestic policy-making. First, emissions factors for the oil and gas industries, including pipeline leakage, are very likely much too low to accurately reflect fugitive methane emissions. Second, we request that EPA expand its reporting of methane emissions using both 20-year and 100-year GWPs as well as report methane emissions in the main text of the Inventory using the GWPs from AR5. And finally, we request that EPA clarify the sources and accuracy of data used to estimate emissions from biomass combustion, particularly for the electricity generation sector.

Commenter: Jeff Zimmerman

Damascus Citizens for Sustainability

Comment: Over the last several years it has become apparent that stray emissions of methane from gas development projects across the United States are increasingly contributing to the greenhouse gas levels and climate change. The purpose of our submissions today to your draft inventory document is to bring to your attention a number of recent (2012-2013) studies and reports providing actual measured emissions of stray methane from unconventional gas development using fracking. The data collected and reported in these publications documents a range of additional scientific information that needs to be factored into the GHG emissions inventory and the resultant impacts of climate change.

Three of these reports document extensive methane leakage from natural gas distribution facilities in Manhattan, New York City, NY, (Payne and Ackley, March 2013) Boston, MA, (Philips et al., 2012) and Los Angeles, CA (Peischl et al., 2013). The LA Basin report documents methane leakage at 17% of total gas production in the LA Basin. Another report provides methane leakage data in a natural gas production area in Wyalusing Township in Bradford County, PA (Payne and Ackley, November 2013) and another report documents methane leakage in fracked gas production areas of Leroy, Granville, and Franklin Townships in Bradford County, PA (Payne and Ackley, 2012). A sixth report documents 4% methane leakage in the Denver-Julesurg Basin in Colorado (Tollefson, 2012), and a seventh report documents a 9% overall methane leakage rate from fracked gas development in the Uinta Basin in Utah (Tollefson, 2013). These reports seriously call into question the much lower methane leakage rates from fracked gas development estimated by EPA. A report by Miller and many others summarizes the results of these and other similar studies and concludes that actual methane leakage rates are almost five times the earlier EPA estimates (Miller et al., 2013). Each of the reports we are providing with this comment letter should be included in the EPA inventory of climate change and GHG data. The trend in these reports demonstrates that methane leakage from unconventional gas development is far greater than previously thought. A comprehensive reexamination of leakage rates and impacts is clearly required.

Commenter: Cynthia Finley

National Association of Clean Water Agencies (NACWA)

Comment: The wastewater treatment category includes publicly owned treatment works (POTWs), septic systems, and industrial wastewater treatment systems. Although the emissions are much smaller in magnitude than for the highest ranked categories, the broadly-based wastewater category consistently ranks in the top ten emitters for nitrous oxide and methane emissions in the U.S. NACWA's review focused on emissions from POTWs, which are a fraction of the total wastewater treatment category emissions.

The emissions from POTWs in the 2012 Inventory are essentially the same as those in the 2011 Inventory, with some clarifications added to the text. NACWA's comments on the 2011 Inventory requested that all values used in the equation to calculate emissions be provided to enable the calculations to be easily reproduced. NACWA appreciates the response to this request with the addition of Table 8-15, which provides the values for the variables used in calculating the nitrous oxide emissions for 2012 and previous years.

Comment: NACWA agrees with the additions made to the Planned Improvements section and encourages EPA to investigate additional data sources as soon as possible. Since the 2008 Clean Watershed Needs Survey (CWNS) is not detailed enough to be used in the Inventory and the 2004 CWNS data is likely outdated, additional data sources are necessary to ensure the accuracy of future Inventories. NACWA supports EPA's investigation of the data available at www.biogasdata.org and from ongoing research in the U.S. and abroad. However, NACWA also urges caution in using results from studies that were not designed to produce nationally-applicable results. Relying on studies that are not representative of utilities nationwide may actually increase the uncertainty of the estimates. NACWA agrees that EPA's plan to review inventories from other countries for additional data and methodologies may be useful, as long as any information used is directly applicable to wastewater treatment processes in the U.S.

Comment: As NACWA has explained in comments on the Inventory in previous years, the Association believes that the nitrogen loading rates for N2OEFFLUENT are sourced incorrectly and that using information from the existing National Pollution Discharge Elimination System (NPDES) database will yield more accurate and justifiable loading rates. The NPDES permitting program represents long-term, nationwide facility performance which would allow emissions estimate projections over the time series represented in the Inventory. If EPA decides not to investigate its own databases, the average nitrogen loading rate of 15.1 g N/capita-day1 represents the industry standard and is supported by a wealth of data widely confirmed in U.S. practice, as explained in our previous comments and supported by data collected by NACWA from 48 U.S. POTWs. This result represents all domestic sources of nitrogen, the use of other nitrogen-containing compounds, and both residential and commercial sources.

Comment: Outside of the Wastewater Treatment section, the Inventory's Executive Summary and Introduction should state more clearly that the Inventory's purpose is for information, not regulation. EPA should ensure that all of its offices understand the purpose of the Inventory and recognize that the Inventory's industry-wide methodologies are largely inadequate for facility level emissions, such as those required by EPA's Greenhouse Gas Reporting Rule and the Clean Air Act Title V and Prevention of Significant Deterioration (PSD) permitting programs.

Commenter: David McCabe

Clean Air Task Force (CATF)

Comment: Methane from Petroleum and Natural Gas Systems:

In our January comments on the Expert draft of the inventory, we raised a number of issues that we summarize here. Although EPA has noted most of the issues we raised in the discussion text of the public draft inventory ("Draft Inventory"), the emissions estimates in that version have not been substantially modified from the expert draft inventory. Consequently, the inaccuracies we identified remain in the inventory estimates. As such, we re-confirm our January comments, which we have attached to this document for your convenience, with some updated figures, and have made additional specific suggestions about how EPA might handle identified inaccuracies in the draft inventories here.

We raised three principle issues in the January comments: Emissions from completion of oil wells with hydraulic fracturing (HF), emissions from completion of gas wells with HF, and emissions from pneumatic controllers (PCs).

In addition we raise two additional issues in these comments: Methane from venting of associated gas from oil wells (during production), and general comments about the approach taken to tabulating emissions in the Inventory.

Comment: Emissions from completion of oil wells with hydraulic fracturing. EPA continues to use a very low emissions factor for oil well completion – 733 scf per completion – that pre-dates the use of HF on oil wells. Since most oil wells are now hydraulically fractured, and the use of HF substantially increases potential emissions per well (just as for natural gas wells), the use of this ancient emissions factor for all oil well completions substantially underestimates actual emissions.

We reference the recent comments from Environmental Defense Fund (EDF) on the Draft Inventory. EDF reviewed data from a number of sources that show that both potential and actual emissions from oil well completions after hydraulic fracturing can be hundreds of times greater than the 733 scf per well completion EPA uses in the Draft Inventory. EDF recommends that EPA use analysis of EPA’s Greenhouse Gas Reporting Program (GHGRP) data for reported emissions from well completions in oil-bearing formations. This analysis finds that reported actual cumulative emissions (including wells where gas was vented, wells where gas was flared, and wells where gas was captured into pipelines, during flowback) were an average of 6.2 metric tons of methane per completion or recompletion, based on reports on 1,754 completions and recompletions. We support EDF’s recommendation that EPA use this data to revise the estimates for well completion of oil wells for wells that use hydraulic fracturing, EDF’s suggestion that oil well completion emissions be reported with sub-categories for wells with and without hydraulic fracturing, and EDF’s suggested approach for estimating the number of oil wells that use hydraulic fracturing.

Estimating methane emissions from oil well completions in this manner would clearly be more accurate than EPA’s current method. EPA must promptly address this rather manifest inaccuracy in the final 2014 inventory. If EPA is unable to provide a more accurate estimate of emissions from oil wells completions in the final 2014 inventory, a statement directly noting this issue is warranted. We suggest adding the following to page 3-55 (suggested additions in bold):

> -line 11: “…increase again with the widespread use of hydraulic fracturing in tight formations.”
> - After the period on line 13. “Note that the inventory methodology has not been updated to reflect emissions during well completion or re-completion after hydraulic fracturing, and thus the inventory likely underestimates emissions from this source.”

Comment: EPA has revised the methodology for estimating emissions of methane from completion of gas wells. As in our January comments, we generally support this revision, as the revised data appears to be based on more robust data and the result is much more transparent. However, as we noted in our January comments, EPA’s methodology is flawed because it fails to account for the significant fraction of gas well completions at facilities that do not report data to the GHGRP. Thus, the activity data reported in table A-126 of the inventory is clearly an underestimate of actual activity. As we suggested earlier, EPA should use data from state databases or commercial databases, compared to reports to GHGRP, to calculate the fraction of wells that are owned by firms that report data to the GHGRP, and then adjust the activity data from GHGRP using this fraction, to get a more accurate estimate of the number of completions occurring nationwide. The suggested approach is described in somewhat more detail in our January comments, as EPA mentions in the Public Draft Inventory (p 3-71, lines 1-3).

Although adjusting the GHGRP to a proper estimate of national activity is not trivial, the current figure is clearly an underestimate of national emissions and we believe EPA would set a poor precedent by using unadjusted data in the Inventory. If EPA chooses not to adjust the GHGRP data, as suggested or by some other approach, EPA should acknowledge in the inventory that the issue exists. Currently, in the Public Draft, this issue is not mentioned directly, but rather is indirectly referred to (in response to CATF comments) under “Well Counts and Completion and Workover Counts” under “Planned Improvements.” It should be raised with a statement to the effect of, “This methodology undercounts emissions from completions and workovers with hydraulic fracturing, to the extent that it undercounts completion and workover events, because not all well facilities report emissions and activity data to GHGRP.” This statement belongs in either the completions text in the QA/QC section, or the completions text in the Recalculations section. Additionally, it would be a great example to list under Uncertainty and Time Series Consistency. For example, starting on line 35 of p 3-66,

> The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." An example would be the probable undercount of completion and workover events with hydraulic fracturing (see below). As a result, the understanding of the uncertainty of emissions estimates for this category will evolve and will improve as the underlying methodologies and datasets improve.

Comment: Pneumatic Controller emissions:

As described in our January comments, GHGRP data shows significantly higher emissions from pneumatic controllers (PCs) than the Draft Inventory reports. Since the GHGRP uses emissions factors derived from EPA/GRI (1996), as does the Inventory, the apparent difference between the two is in device counts. Although the GHGRP clearly undercounts devices (by not capturing all wellpads, or any emissions from gathering), it must be more accurate than the current activity figures used in the Inventory. As noted in our January comments, since not all wellpads report under the GHGRP, it shows that total emissions from oil and gas wellpads were, at a minimum, 861 Gg methane in 2012. The Public Draft reports emissions from both Gas Production and Oil Production of 692 Gg methane, less than was reported in the Expert Draft (787 Gg methane), so this gap has widened significantly. While we recognize that updated activity data for 2012 may increase the figures in the Inventory, relative to the Public Draft, we anticipate that the gap between the Inventory figure and the GHGRP figure will remain: for 2011, the Public Draft Inventory reports emissions of 752 Gg methane from oil and gas production, while the GHGRP data shows 835 Gg methane. Again, this is troubling because the GHGRP only covers a portion of the facilities that the Inventory is intended to cover yet its emissions figures are higher than the Draft Inventory.

As mentioned in our January comments, the gap would be much larger if the more accurate emissions factors from the Allen et. al (2013) study were used in place of the GHGRP emissions factors. The data available today suggests that the Allen et al. emissions factors are the best available today. As described in our January comments, correcting the GHGRP with the Allen et al. emissions factors produces a national methane emissions estimate of 1,140 Gg, even without scaling emissions up to reflect production facilities that do not report to GHGRP.

Thus it appears that both the activity data and emissions factors used in the inventory for PCs are not the most accurate data available. If EPA cannot use the more accurate, recent data we have suggested here, EPA should continue to note that data (as is done in the Public Draft) and commit to examining this data in the coming year.

Comment: Venting of Associated Gas from Oil Wells:

It appears that the Inventory underestimates venting from oil wells by a substantial amount. To our understanding, venting of associated gas from oil wells during production (i.e., casinghead gas venting) is listed in the inventory as “Stripper Wells” under Vented Emissions in Petroleum Production, and is listed as 14.2 Gg methane for 2012. Last year’s inventory listed the same value for 2011.

GHGRP data shows much higher emissions of methane from “Associated Gas Venting and Flaring.” For 2011, 175 Gg methane emissions were reported to GHGRP; for 2012, the figure was 90 Gg. Some of this is due to emissions of methane from flares, due to incomplete combustion in the flame. This portion of the methane emissions can be accurately estimated, by comparing CO2 emissions from associated gas venting and flaring to methane emissions from that source. As described below, CATF analyzed the GHGRP data in this way, finding that 60% to 90% of the GHGRP methane emissions from associated gas venting and flaring are due to venting, and thus the 14.2 Gg methane figure in the Draft Inventory is significantly too low.

We compared the emissions of CO2 and CH4 reported from each facility reporting “Associated Gas Venting and Flaring” emissions to the GHGRP, for both 2011 and 2012. The GHGRP uses a default factor of 2% for emissions of methane from flares, due to incomplete combustion (40 CFR Part 98.233(n)(1), Eq. W-19). Using this factor, we subtracted away the maximum methane that could be due to incomplete combustion in flares from each individual facility report. To be conservative, we also considered a case where the factor for incomplete combustion for methane in flares was 5%, in case some facilities used this higher factor to calculate their emissions.

In either case, many facilities have methane emissions well in excess of that due to incomplete combustion, and this "excess methane," which is due to venting of associated gas, is significant at the national level. In 2011, vented emissions, calculated with the 2% emissions factor, were 157.5 Gg methane; in 2012 they were 60.1 Gg CH4. Raising the incomplete combustion factor to 5% drops these figures somewhat, to 154.0 Gg CH4 and 56.3 Gg CH4, respectively. This analysis of the GHGRP data shows that venting of associated gas from oil wells is much higher than the 14 Gg reported in the Draft Inventory.

Comment: General Comments on the Organization of the Inventory for Oil and Gas:

As new data emerges on emissions from oil and gas facilities, it is very important that EPA use that data in the most appropriate way in the inventory. In some cases it may not be best for EPA to force the data into the framework used in the inventory, particularly where a) oil and natural gas production are separated and b) natural gas production is broken down, for almost every individual source, into NEMS regions.

It is appropriate that EPA has not developed emissions factors for each NEMS region for well completion and workover with HF, and it greatly improves the clarity of the inventory that these emissions are presented separately in Table A-126. We believe that EPA should have taken the same approach last year when updating the methodology for estimating liquids unloading (LU) emissions. The report submitted by API and ANGA on LU emissions did not recommend developing distinct emissions factors for each NEMS region for wells that vent during LU with and without plunger lifts. Instead, API and ANGA concluded it was more appropriate to estimate national emissions by applying their entire dataset to national activity drivers. EPA, in calculating emissions for each NEMS region, concludes that national LU emissions were substantially lower than API and ANGA concluded. Moreover, the calculated emissions factors for LU wells vary tremendously between NEMS regions that are not designed to capture differences in geology, age of wells, or anything else that might affect LU emissions. The NEMS region emissions factors are simply not credible.

EPA should use the national emissions factor approach used for completion / workover emissions for LU.

Additionally, when data from the GHGRP is superior to other available data, EPA should use that data, even if it does not readily allow separation of emissions between the oil production and natural gas production sectors. As EPA has recognized in, for example, GHGRP Subpart W and NSPS Subpart OOOO, these sectors are really one industry, and the distinction between the two is necessarily arbitrary. At present the Inventory reports that over 60% of emissions from PCs are from oil production, so it may be more appropriate to simply list PC emissions under oil production, with the "included elsewhere" designation for PCs under gas production.

Finally, we comment here on the Draft Inventory's discussion of Methane Measurement Studies (p. 3-71). First, we note that the Brandt et al. study mentioned in this section is quite specific that emissions from oil and natural gas, specifically, were underestimated in the 2013 Inventory (which reported higher emissions than the Draft 2014 Inventory. Quoting from Brandt et al.: "We find … measurements at all scales show that official inventories consistently underestimate actual CH4 emissions, with the NG and oil sectors as important contributors…" (emphasis added). The title of Brandt et al.'s paper is "Methane Leaks from North American Natural Gas Systems." The Draft Inventory's over-generalization of Brandt et al.'s findings must be corrected.

EPA asks for input on how information from top-down ambient studies should be used to update the inventory. One non-quantitative way that EPA should use this information is to put the bottom-up inventory in context. The bottom-up inventory is essential for understanding the specifics of GHG emissions so that mitigation priorities, for example, can be examined. However, the bottom-up inventory clearly does not capture all emissions from oil and gas operations. Scientifically, it is not clear that the emissions from the sector as a whole are most accurately measured with the bottom-up measurements available to date. As such, it may be appropriate to calculate the leak rate from the entire industry (for life-cycle analysis, for example) using different methodologies. Separately, as ambient studies continue and techniques are developed, they will illuminate sources that must be reexamined in bottom-up studies. For these reasons, the top-down methodologies are strongly complementary to the bottom-up approach.

It would be appropriate for EPA to mention, in this section, the value of top-down studies in providing independent data on overall emissions from the industry, and on identifying specific potential issues in the inventory.

Comment: Emissions Data for Wood Biomass Combustion:

CATF requests that EPA provide a clearer explanation of the data on CO2 emissions from wood consumption reported in section 3.10 of the Draft Inventory, particularly the data that are reported for electricity generation units (EGUs). EPA describes the approach it used to determine the amount of CO2e emitted by EGUs that combust woody biomass in the Methodology passage at 3-79 of the Draft Inventory, but it is difficult—if not impossible—to replicate the results that EPA achieved using the database referenced by the Agency.

According to CATF's understanding of the Methodology passage at 3-79, EPA has determined that the Acid Rain Program's "bottom-up" data for woody biomass consumption by EGUs are better than the EIA Monthly Energy Review data for those same sources. EPA made the same determination in the 2013 US GHG Inventory of Emissions and Sinks, but neither the 2013 Inventory nor the 2014 Draft Inventory explains the Agency's preference for the Acid Raid data. (Id.; 2013 Inventory at 3-79). The lack of an explanation is particularly problematic because, notwithstanding its concerns about the EIA data for woody biomass consumption by EGUs, EPA considers EIA's national estimate for total woody biomass consumption to be accurate. (2014 Draft Inventory at 3-79). In any event, EGU biomass consumption data for 2012 is lower in the

Acid Rain dataset than it is in the EIA dataset. So in order to use both the Acid Rain data for woody biomass consumption by EGUs and the EIA data for total national consumption, EPA adjusts the consumption/emissions data for the other three sectors (Industrial, Residential, Commercial). (Id). It appears that that EPA calculated the difference between the EIA data and the Acid Rain data for woody biomass consumption by EGUs and then proportionally allocated that difference to those other sectors' EIA scores.

Assuming that is in fact how EPA determined the woody biomass consumption and emissions data reported in Tables 3-55 and 3-56, CATF was unable to reproduce the reported results for the Electricity Generation sector using the ampd.epa.gov database — which in turn prevented us from assessing the reported results for the other three sectors. We note, however, that the reported EGU emissions for 2012 (21.0 Tg CO2e) are an order of magnitude higher than they were in 2008 (2.8 Tg CO2e), 2009 (2.4 Tg CO2e), 2010 (2.6 Tg CO2e), and 2011 (2.4 Tg CO2e). (Draft 2014 Inventory at 3-78, Table 3-55). We also note that emissions from EGU consumption of woody biomass reported during earlier years (e.g. 2008-2011) appear to be too low when compared to emissions data that CATF received in response to queries at ampd.epa.gov. Finally, CATF notes that Acid Rain database appears to be significantly under-inclusive. For example, when CATF queried the database for national CO_2 emissions from EGUs that combust "wood" and "other solid fuel," the result was comprised of emissions from only a handful of facilities located in just five states.

Comment: Discussion and Presentation of Global Warming Potentials (GWPs) from IPCC's Fifth Assessment Report in the introduction and Annex 6.1:

In the Draft Inventory, EPA has presented the GWPs from IPCC's Fifth Assessment Report (AR5) incompletely. We commend EPA for committing to using the GWPs from the 2007 Fourth Assessment Report (AR4) in next year's inventory, in compliance with UNFCCC guidelines. However, the more recent AR5 GWPs are now considered more accurate, and it is important that EPA let readers know about these updates. The material presented in the Introduction, and in Annex 6.1, does not accurately report what AR5 reports for GWPs, and the problem is particularly acute for methane from "fossil" sources such as coal, oil, and natural gas.

For all GHGs, AR5 reports two GWPs. For one, the climate carbon feedback ("cc-fb") effects are included when the radiative forcing from the target gas (the non-CO2 GHG) is calculated; for the other GWP, the cc-fb are not included in this calculation. However, GWPs are calculated relative to the radiative forcing caused by CO2, and the cc-fb is included for the calculation of radiative forcing from CO2 in all GWP calculations. That is, when the GWP for methane is calculated "without the cc-fb," the radiative forcing for methane without the cc-fb is compared to the radiative forcing for CO2 with the cc-fb. For this reason, IPCC states that it is likely that the GWPs with the cc-fb included are more accurate. (See page 731 of AR5). As such, the Draft Inventory, which only presents AR5 GWPs without the cc-fb, (Draft Inventory at 1-9, Box 1-2) is not presenting the most accurate information to readers.

Furthermore, specific to methane, EPA should also include the GWPs that IPCC calculates for fossil methane. The table on page 1-9 omits this. There is no reason not to include the GWP for fossil methane in the table. While the issue was not properly handled in earlier editions of IPCC Assessment reports, it is a simple matter: CO2 from the oxidation of fossil methane is additional CO2 in the climate system, whereas CO2 from oxidation of biogenic methane is not. EPA must report the best available scientific information. Consistency with earlier, less accurate IPCC reports, is not an acceptable reason to leave this information out of the Table. After all, it is just an informational table. However, many users will read this table to read that AR5 says the GWP of CH4 is 28, period. The notes at the bottom of the table are not sufficient.

In summary, a line should be added for fossil methane. It would have no entries for SAR, TAR, or AR4, so it would be clear that it is new, and that there is no analogue in the previous ARs. Secondly, an additional column with the AR5 GWPs with the cc-fb included is needed.

Likewise, Annex 6.1 is quite helpful, but it appears to not even acknowledge the GWPs in AR5 calculated with the cc-fb included, nor the separate GWPs for fossil methane. Thus, it is not accurately using the recommendations of AR5.

For example, natural gas, petroleum, coal mines & abandoned coal mines, stationary & mobile combustion, petrochemical and iron/coke production together account for 43% of US methane emissions. Thus, if using the GWPs without the cc-fb included, the correct change to methane emissions (in CO2e) for AR5, relative to AR4 (table A280), would be (5 * 0.43 + 3 * 0.57) / 25 or 15.4%, not the 12% reported in table A280. As mentioned above, AR5 says that it is likely that the values with the cc-fb included are more accurate, so the more accurate GWPs are actually 34 for biogenic methane and 36 for fossil methane. Therefore the most accurate value for the change to methane emissions (in CO2e) for AR5, relative to AR4 (table A280) would be (11 * 0.43 + 9 * 0.57) / 25 or 39%. That's a significant difference, and ignoring all of these other values for GWP does a real disservice to readers of this section.

Therefore, tables A276, A280, A281 should be updated to use the fossil methane GWP for those sources, and to discuss and show the differences if the GWPs with cc-fb included (for all non-CO_2 GHGs) are included.

Comment: Minor Suggested Corrections / Clarifications (by page number)

Page ES-14, Line 13: Strike “observed.” The drop in emissions is inferred, largely from changes in activity drivers.

Page 1-6: Suggest the following addition (in bold):

> “Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds and/or methane mixing with NOx in the presence of sunlight.”

Page 1-9 Box 1-2: In the GWP discussion in the ES, the importance of forcing by secondary products of primary forcers is mentioned. Updates to the calculations of forcing by secondary products is an important factor in the changes in GWPs in AR5. Suggest the following addition (in bold):

> "In the AR5, the IPCC has applied an improved calculation of CO2 radiative forcing and an improved CO2 response function in presenting updated GWP values. IPCC also applied updated calculations of indirect radiative forcing for some gases. Additionally, the atmospheric lifetimes of some gases have been recalculated, and updated background concentrations were used. In addition, the values for radiative forcing and lifetimes have been recalculated for a variety of halocarbons, which were not presented in the SAR."

Page 1-10 Very end of section 1.1, Add this sentence (copied from ES):

> "The use of IPCC AR4 GWP values in future year inventories will apply across the entire time series of the inventory (i.e., from 1990 to 2013) in next year's report."

Page 3-70, line 1: the correct table reference is Annex Table A-135

Page 3-71, line 16: The Brandt et al study is not listed in the References section. Also, please make an effort to provide a URL, whenever possible, to all of the documents listed in the References section, particularly EPA documents.

Tables A125-A130 reference a number of documents not listed in the references section on pp A200-A202. EPA should attempt to get as many of the memos and other documents listed as references onto the website, and provide hyperlinks to those documents in the references section!

Table A125: the EF for Liquids Unloading w/o plunger lifts for region MC is messed up (it is written as 190,17 scfy/well, so either a digit is missing or the comma is in the wrong place.

There are no references listed for the petroleum section. (And a lot of other sections. Maybe those works are cited at the end of Annex 3?)

Commenter: Darren Smith

Devon Energy

Comment: Due to our position as an early-adopter of reducing emissions from production processes, Devon holds unique knowledge about the processes involved and the physical phenomena that shape emissions for hydraulically fractured wells. It was this expertise and knowledge – and the resulting discovery that EPA's previous estimates for methane emissions from the flowback of hydraulically fractured wells were heavily inflated – that led Devon to take an active role in encouraging EPA to refine the previously adopted emission factor for hydraulically fractured wells. It is this same expertise that leads Devon now to commend EPA for the proposed changes in the 2012 Draft GHG Inventory. The proposed changes to this year's inventory have brought the inventory one step closer to an accurate and complete emissions profile for the natural gas production sector.

Comment: Devon supports the use of the Greenhouse Gas Reporting Program for this emission factor, replacing the previous estimate based on Natural Gas Star Data, which was not fit for the purpose of establishing emission factors. Devon has provided numerous comments criticizing the previous emission factor for methane emissions from the flowback of hydraulically fractured wells. The crux of the criticism was that Natural Gas Star recovered volumes were used as a proxy for emissions from vented well completions. Natural Gas Star data is not fit for emission factor determination. This new method drastically improves accuracy of the factor, and can form the basis for making adjustments to the inventory in the future, as industry technology continues to reduce emissions in the oil and gas sector. While there is still room for improvement due to the GHGRP's use of the choke flow calculation methodology, the change represents a significant improvement in accuracy.

More importantly, through the adoption of net emission factors, EPA provides a framework by which future greenhouse gas reporting rule results can be used to continually refine the emission factors for methane from hydraulically fractured well completions. As the greenhouse gas reporting rule further refines its calculation and reporting methodologies, and as industry improves its technology and practices to further reduce emissions, the emission factors for methane from well completions can and should be adjusted accordingly. Given that net emissions factors will closely mimic GHGRP data, updates to the emission factor can be easily automated, so that an accurate emissions profile can be captured each year. Finally, creating net emission factors that more closely match the GHGRP data will provide the public confidence in the accuracy of this particular data program.

This potential, and the ability for the public to verify greenhouse gas reporting program data, provides transparency to the method by which the factors are determined. This allows policy makers and the public to better understand the different emission profiles for different equipment configurations, and for the federal and state governments to make policy decisions based on accurate data.

Commenter: Erica Bowman

America's Natural Gas Alliance

Comment: ANGA appreciates the changes EPA has made in developing the 2014 Draft GHG Inventory, which incorporates new data sources and methodologies that more accurately reflect actual emissions. These changes include the establishment of technology-specific emissions factors for wells with hydraulically fractured completions and workovers. We encourage EPA to continue upgrading the GHG Inventory with net emission factors in place of potential emission factors as more data become available. We would also support further sub-categorization to recognize the differences between hydraulically fractured completions and hydraulically fractured workovers.

Comment: For the past several years, ANGA has submitted comments on EPA's Draft GHG Inventories. Included in those comments were concerns that EPA has overestimated emissions from natural gas production activities, particularly emissions associated with the liquids unloading, and well completions and workovers. In the 2013 GHG Inventory, EPA adjusted the methodologies for estimating the frequency of well re-fracturing and emissions from liquids unloading. These changes contributed to a reduction in estimated 2010 Field Production emissions from Natural Gas Systems of 54 percent. ANGA supported these changes, which more accurately accounted for actual field practices.

In the 2014 Draft GHG Inventory, EPA adjusts the methodology for completions and workovers with hydraulic fracturing. These adjustments establish four technology-specific emissions factors for wells with hydraulically fractured completions and workovers: (1) hydraulic fracturing completions and workovers that vent; (2) hydraulic fracturing completions and workovers that flare; (3) hydraulic fracturing completions and workovers with Reduced Emission Completions (RECs); and (4) hydraulic fracturing completions and workovers with RECs that flare. These emissions factors are based on data submitted to EPA under the 20 II and 2012 Greenhouse Gas Reporting Program (GHGRP) Subpart W. Compared to data used in the 2013 GHG Inventory, the GHGRP data shows a higher percentage of hydraulically fractured well completions and workovers using RECs, a higher percentage of hydraulically fractured well completions and workovers that flare, and fewer emissions per hydraulically fractured completion and workover that vented. We believe that the adjustment to the emissions factor for hydraulically fractured well completions and workovers that vent is closer to representing actual emissions. The GHGRP data used by EPA support ANGA's long-held contention that EPA's estimate that 9,000 thousand cubic feet (Mcf) of natural gas is released per uncontrolled well completion is flawed due to its reliance on data from the Natural Gas STAR program.

Comment: Although the new emission factors for uncontrolled well completions better represent actual industry practices, they remain higher than measured results from the recent study by researchers at the University of Texas-Austin and supported by Environmental Defense Fund (UT Austin/EDF study). At 41 metric tons (MT) methane per vented well completion, for example, the estimate in the Draft 2014 GHG Inventory is within one order of magnitude of the range found for similarly configured completions in the UT Austin/EDF Study, which found a range of 0.5-4 MT methane per completion event for those wells vented directly to atmosphere. Much of this difference can be attributed to the choke flow calculation methodology option in the GHGRP. The choke flow calculation methodology was not designed for use in multi-phase flow applications, and as such can often deliver erroneous results when compared to direct measurement. ANGA encourages EPA to remove outlier data from the emission factor calculation and use only measured data in the GHGRP for the calculation of emission factors, not data derived from the choke flow equation methodology.

Comment: As noted above, ANGA supports the use of GHGRP data to establish emission factors and strongly believes that EPA should continue using this data source to refine the emission factors for hydraulically fractured well completions and workovers. As industry technology and practices improve to further reduce methane emissions and the GHGRP continues to update its calculation and reporting methodologies, the emission factors for hydraulically fractured wells and completions should be adjusted accordingly. In addition to improving the accuracy of the GHG Inventory which is a common goal of both EPA and the natural gas industry, creating emissions factors that more closely match the GHGRP data will provide public confidence in and increase uniformity across EPA's data programs.

While ANGA continues to believe that EPA's estimate of the number of uncontrolled well completions and workovers is too high, we understand that this number will decrease significantly in future years as the 2015 and later GHG Inventories will factor in the REC and completion combustion device requirements included in the Oil & Gas New Source Pollution Standards. This rule requires the use of RECs for almost all completions and workovers after January 1, 2015 and required flowback emissions to be routed to a completion combustion device starting in October 2012. As a result, the 2015 GHG Inventory, which reports estimated emissions from 2013, should have significantly lower emissions from these activities.

Comment: In response to EPA's request for input on the assumptions regarding the historic use of RECs, we support the recommendations made by Devon in its comments on the expert review draft and public review draft of the 2014 GHG Inventory. As EPA considers other changes to the inventory, we would support sub-categorization of pneumatic controllers to high bleed, low bleed, and intermittent categories and the use of appropriate actual emission factors for each category using GHGRP data, the UT Austin/EDF study, and other recent and upcoming studies.

Comment: Given the magnitude of the changes that the Agency has made over the past four years both increasing and decreasing estimated emissions from natural gas production, the underlying data and assumptions must be rigorous and well supported. ANGA appreciates the changes EPA has made to its methodology for estimating emissions from liquids unloading, its estimate of the frequency of work overs, and its methodology for hydraulically fractured well completions and workovers. We encourage EPA to continue updating its methodology and emissions factors with technology- and region-specific emissions factors based on valid data, assumptions and calculations. However, given the underlying uncertainties of the current data, ANGA does not support the use of the emissions estimates presented in the GHG Inventory as the basis for any analysis or regulatory action.

Commenter: Karin Ritter

American Petroleum Institute

Comment: General:

API supports the changes made to the 2012 U.S. GHG Inventory including the advances made in updating the national emission estimation methodology and increased use of site specific industry data that is becoming available through the Greenhouse Gas Reporting Program (GHGRP). When accounting for these changes the resulting non-combustion emissions from

Natural Gas Systems are estimated to be 162.3 million metric tonnes of CO2e (CO2 - 35.2; CH4 - 127.1). This represents a 1.07% of natural gas withdrawals for 2012. API encourages EPA to state this clearly early in the discussion on Natural Gas Systems to enhance understanding of the data by potential users.

Comment: General:

For this Public Review of the draft 2012 national inventory, API is providing comments regarding emission estimation for Petroleum Systems and Natural Gas Systems. Our comments reiterate some of the discussions on recalculations that were part of the U.S. GHG Inventory expert review phase and also point out areas for future collaboration where EPA is planning future improvements. API supports further review and analysis of the GHGRP data with the overarching goal of ensuring the quality and validity of data being used for deriving new national emission factors.

In addition, results from on-going GHG emission studies are expected to be published this year, and API is willing to continue its collaboration with EPA to incorporate relevant new information in the 2012 U.S. GHG Inventory and beyond.

Comment: General:

API supports the continued disaggregation of emission source information and, if applicable, emission reductions, to provide better transparency for “net” emissions for each source type. The approach historically used by EPA of lumping together reduction activities for multiple inventory sources made it difficult to attribute these reductions to specific inventory source categories. Emission reductions reported for “Other Production”, “Other Processing”, “Other Transmission” and “Other Distribution” in Table A-135 are larger than those shown in the Expert Review Draft and provide less transparency about the sources of these emission reductions.

Comment: General:

Where appropriate for the source category, API supports the continued use of data reported through the GHGRP and other relevant “bottoms-up” studies to develop “net” emission factors for specific source categories. API also recommends that EPA recalculate “net” emission factors for relevant source categories on an annual basis, using the GHGRP data and any relevant new “bottoms-up” studies, for each successive inventory in order to reflect changes in emissions due to expanded regulatory and voluntary reductions. This allows EPA to highlight, in the U.S. GHG Inventory, changing operating practices due to regulatory requirements being phased in by the petroleum and natural gas sector over the next few years.

Comment: General:

API advises EPA to carefully analyze and screen GHGRP reported data to identify data outliers and enable verification and/or correction or exclusion of suspect data entries and prevent the use of incorrect data in the derivation of emission factors (EFs). As discussed previously with EPA, during the Expert Review phase, the GHGRP data may potentially include incomplete or incorrect data due to ambiguity in implementation of approved EPA procedures, errors in applying the GHGRP calculations, faults in data aggregation and reporting, and partial reliance on Best Available Monitoring Methods (BAMM). Despite these discussions and detailed analysis provided to EPA to highlight the impact of erroneous data and outliers it seems that EPA did not modify their calculations published in the Public Review version of the 2012 inventory now under consideration.

Comment: Petroleum Systems Emissions:

Page 3-54 and Page 3-55. Editorial Comment:

API has noted a redundancy in the text presented in rows 28-32 of page 3.54 with rows 10–13 of page 3.55.

Comment: Petroleum Systems Emissions:

Page 3-59. Recalculation Discussion: Accounting for Voluntary Emission Reductions:

Under its recalculation discussion EPA seeks comment on its update to the Petroleum Systems section to include Natural Gas Star reduction data. EPA has added an accounting for voluntary emission reductions to the CH4 emissions from Petroleum Systems, and it indicates that this is from reassigning reductions that were previously included under the Natural Gas Systems (as referenced on page 3-70).

API supports this change but notes that the reductions attributed to the Petroleum Systems lacks the level of transparency that was previously provided for Natural Gas Systems. To address this, API recommends that Section 3.6 for Petroleum Systems in the annex should include a table that is equivalent to Tables A-135 and A-136 in the Natural Gas Systems.

Comment: Petroleum Systems Emissions:

Page 3-59. Planned Improvements Oil Well Completions and Workovers:

EPA is discussing its planned improvement to the U.S. GHG Inventory for oil production to allow for differentiation between completions with and without hydraulic fracturing. EPA is seeking comments on the topic as part of its future improvements effort since comments they received during the Expert Review phase indicate that 75-90% of all new oil wells are completed with hydraulic fracturing. Some commenters suggested that updated emission factors could be developed using data from recent studies and EPA is quoting a wide range of potential average emission factors that are being considered without providing any explanations or justifications for these emission factors:

- 6.2 Mg CH4 (GHGRP based on gas well completions and workovers in Oil formations for wells with and without control);
- 3.1 Mg CH4 (UT Austin/EDF; wells with controls);
- 9.7 and 24.7 Mg CH4 (Wattenberg and Eagle Ford data, wells without control)

API wants to emphasize that existing data from recent field studies or from extrapolation from gas wells in oil formations do not provide a reliable representation of potential emissions from oil well completions and workovers. API is willing to work with EPA to assess data that may be used for future improvements of the emission factors used to characterize this emission source.

Comment: Petroleum Systems Emissions

As an additional item for future improvement, EPA is repeating its requests from the Expert Review draft for data on the Oil wells refracture rate, which EPA currently assumes to be 7.5% per year. As previously stated API concurs that field data for Oil well completions with and without hydraulic fracturing is currently sparse. However, EPA's assumption of a 7.5% workover (or refracture) rate for all oil wells seems higher than is expected based on industry's experience.

API is willing to work with EPA to develop a reasonable oil well refracture rate for potential use in future inventories.

Comment: Natural Gas Systems Emissions

Page 3-69. Recalculation Discussion: Gas Wells Completions and Workovers: Alternative Approach to Emission Factors Categories:

During the expert review phase of the U.S. GHG Inventory API supported EPA's derivation of new Emission Factors for gas wells completions and workovers utilizing GHGRP data. API has also noted the need for careful screening of reported data to make sure that erroneous entries and outliers are not used in these calculations.

Moreover, API has recommended that EPA collapse the proposed four categories for grouping gas well completions and workovers with hydraulic fracturing into only two categories. Therefore, in response to EPA's request for comments during the Public Review phase of the inventory, API reiterates its previous comments and maintains that the future relevance of the four distinct operating practices for which EFs were derived ought to be reconsidered. Newly proposed changes to estimating and reporting emissions for flowback events for hydraulically fractured completions and workovers1 and the phasing in of compliance with the Oil and Natural Gas (NSPS)2 will likely result in few to no events without reduced emissions completion

(RECs), and those with RECs will generally include both venting and flaring for short periods of time.

As described before, API is proposing an alternate two-category approach that may be adopted for future inventories and which would entail the derivation of emission factors that are representative of completions and workovers with hydraulic fracturing and limit significant changes in subsequent inventories in view of the expected operational changes:

- Non-REC Completions and Workovers (Vented only); and
- REC Completions and Workovers (vented and flared).

Table 1 below reintroduces a modified version of the EFs from such an alternative approach, as provided by API during the expert review phase of the U.S. GHG Inventory. The results are presented for both the 2011 and 2012 GHGRP data (with outliers removed) and these two categories are expected to provide a good characterization of emissions from these emission sources and will enable tracking industry's transition to the use of reduced emission completions and workovers. Based on discussions with EPA it became clear that EPA's count of vented completions and workovers without RECs includes completions with zero emissions. API's initial calculation approach excluded these data sets for the non-REC completions and workovers. This has been revised in API's modified analysis shown in Table1. For 2012, 466 non-REC vented completions and 95 non-REC workovers were reported with zero emissions.

Year	Category	Total CH4 Emissions, tonnes CO2e	# events	Tonnes CH4/event	Scf CH4/event	# data sets
2012 Data	Non-REC Completions and Workovers (Vented only)	1,121,164	3,037	17.58	915,596	252
	REC Completions and Workovers (vented and flared)	219,364	3,051	4.21	269,854	333
2011 Data	Non-REC Completions and Workovers (Vented only)	2,803,608	2,957	45.15	2,351,503	346
	REC Completions and Workovers (vented and flared)	430,161	4,815	4.25	221,572	319

Comment: Natural Gas Systems Emissions

Page 70. Planned Improvements: Completion and Workover Counts:

In its discussion about future Planned Improvements, EPA is addressing issues that were brought up repeatedly in API's discussions with EPA. API has provided comments before about the inconsistency in accounting for the total number of completions and workovers, due to ambiguous language in the GHG Reporting Program.

At EPA's request, API has surveyed its members and summarizes below the findings that point out the differences between EPA and API's completions and workover counts, which impact the calculated emission factors.

- EPA assumed the number of completions is equal to the sum of total completions reported and completions with purposely designed separating equipment (RECs). API assumed the RECs were a subset of the total completions reported. This was confirmed by seven (7) member companies.
- EPA assumed the number of workovers is equal to the sum of vented workovers, flared workovers, and REC workovers. API assumed the total number of workovers was equal to the sum of the vented and flared workovers, and that workovers with purposely designed separation equipment were a subset of this total. This was confirmed by five (5) member companies.
- Where data sets provided a count of workovers with REC, but no count of vented or flared workovers and zero emissions, EPA assigned these as vented workovers with REC. API treated these as invalid data sets. For 2012, this applied to 11 data sets, representing 21 workover events. The API analysis has been revised to include these data sets, as reflected in Table 1 above.

Comment: Natural Gas Systems Emissions

Page 3-71. Planned Improvement: Methane Measurement Studies:

EPA is requesting feedback on how measurements from top-down studies can be used to update its emissions estimates. As API stated before, studies such as Petron 2012 and Miller et al. 2013 focus on inverse flux modeling which employs emission concentration data from aircrafts, ground-based or towers over a regional area or on ambient hydrocarbon species ratios analysis. These studies have either been regional and do not fully represent natural gas production in the US (e.g. Petron 2012), or do not represent current operations (Miller 2013 and Petron 2012). Additionally, these studies are a "snapshot" in time and do not necessarily give any indication of emission rates over a longer time period such as annual. It is well know that bottoms-up methods like Allen et al. have much better accuracy over top-down methods. Since EPA's greenhouse gas inventory, uses a bottoms-up approach in itself, especially for quantifying CH4 emissions, it is more appropriate to use other bottoms-up approaches as data sources and for inventory verification.

There are several studies underway that attempt to combine top-down and bottoms-up methods to better understand and reconcile the differences. Until such time, EPA should only consider studies that measure emissions directly from the individual sources or activities.

Additionally, API wants to reiterate that no top-down study will be able to produce granular level information provided by the EPA inventory with respect to individual sources or activities within a sector. At best, these top-down methods can be used for gross verification of the inventory estimates.

Comment: Comments on Appendix A, Table A-135:

EPA has revised the voluntary emission reduction data in the table. The "other production" category increased from 40 Gg CH4 in the expert review version to 619.3 Gg in this version. There is no explanation of the change in reductions other than EPA reallocated some from the natural gas systems to petroleum systems.

API contends that this change is a step backward in the transparency of the emission reduction data and urges EPA to elaborate on how the change was calculated and what it includes. This does not apply only to the onshore production segment since the same increase is noted in the "other" reductions for the other industry segments listed in Table A-135.

Comment: Comments on Appendix A, Table A-141:

There seems to be an error in Table A-141. API's recalculation of the production sector emissions indicates that the value shown for condensate tanks in this table (2252 Gg) is not the net emissions. The net emissions for this source should be 164.9 Gg CH4.

Comment: Comments on Appendix A, Table A-143:

EPA revised the emission estimate for CO2 from flares. While in the Expert Review version 9,868.6 Gg CO2 were reported (Table A-141) in this version we note a value of 12,738.8 Gg (Table A-143). This appears to combine flaring from production and processing operations. API is requesting that EPA explain this new value and state specifically what industry segment it represents, or break out emissions associated with production operations separately from processing.

Comment: General Editorial:

API suggests that EPA keep the same order for the emission sources in the tables presented for each industry sector. This would certainly help when reviewing tables side by side. For example, EPA has moved the location of the emissions for gas well workovers among the different tables. In Table A-125, these emissions are presented with completions and well drilling, while in Table A 1-43, workover emissions are presented separately after tanks.

In summary, API appreciates the opportunity to provide comments during the public review phase of the 2012 U.S. GHG Inventory. EPA noted some errors and omissions that need to be addressed prior to finalizing the inventory while reiterating comments provided during the Expert Review phase and indicating areas for potential future improvements.

Commenter: David Isaacs

Semiconductor Industry Association

Comment: The current IPCC guidelines were established in 2006 with data collected in 2004 and earlier. While the data used to devise these methods represented the best available data at the time, it no longer represents the most accurate data available. The default emission factors contained in the current IPCC guidelines were based on 75 emissions characterization data sets, which may no longer be representative of the processes and equipment used throughout the industry.

Comment: In 2013 EPA issued a final rule governing the reporting of greenhouse gas emissions for the semiconductor industry in the United States, codified at 40 C.F.R. Part 98 Subpart I. As part of the development of this regulation, SIA member companies, several process equipment manufacturers, and SEMATECH, contributed to a large data collection effort resulting in a substantial amount of new data. The participants in this data collection undertook an extensive effort to characterize the processes deployed in our industry. The data collected was from equipment processing different wafer sizes and multiple semiconductor companies and equipment suppliers. It includes every fluorinated greenhouse gas currently used in semiconductor plasma etch processing and chemical vapor deposition chamber cleaning. The new data brings the total number of data sets to 1182.

SIA believes that the additional data used in the development of Subpart I will result in more accurate and more representative reporting of PFC emissions from semiconductor fabs in the United States as compared with the current IPCC guidelines used internationally to report emissions from our industry. EPA evidently concurs with this conclusion through the adoption of the regulation. Therefore, in order to improve the reporting of emissions globally and ensure consistency in reporting methods, SIA requests that EPA work to update the current IPCC guidelines to reflect this new data. Updating the IPCC guidelines will improve the consistency of the data contained in the U.S. inventory with the information available globally, and also improve the accuracy of the global data. SIA would be pleased to assist EPA in this endeavor.

Commenter: David Lyon

Environmental Defense Fund

Comment: Environmental Defense Fund (EDF) previously submitted comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012 (Draft 2014 Inventory) during the expert review comment period. As stated in our previous comments, we recommend that EPA updates the Petroleum Systems source category to account for methane emissions from co-producing well completions with hydraulic fracturing. EDF has prepared a white paper on methane emissions from co-producing well completions that summarizes our analyses of several recent data sources including the Greenhouse Gas Reporting Program Subpart W, Allen et al. 2013, and initial production data from the Eagle Ford, Bakken, and Wattenberg fields. Based on these analyses, we estimate that 2012 methane emissions from co-producing well completions are between 96 and 247 Gg CH4, comparable to the Draft 2014 Inventory estimate of 217 Gg CH4 emissions from hydraulically-fractured gas well completions and workovers.

Commenter: Nathan Matthews

Sierra Club

Comment: The Sierra Club files these comments on the February 2014 draft 1990-2012 Greenhouse Gas Inventory. We offer the following concerns:

- For gas production, although EPA proposes to revise sector wide emissions estimates downward, recent science based on atmospheric measurements indicates that a strong upward revision is appropriate.
- The "UT Austin EDF" Study provides further indication that the inventory's estimate of gas systems emissions is too low. Emissions from pneumatic controllers, in particular, are likely to be underestimated.
- The draft inventory does not include emissions from unconventional (e.g., hydraulically fractured) petroleum wells.
- EPA's outdated figure for methane's global warming potential is far lower than recent estimates.

Comment: Atmospheric Studies Indicate That Gas Systems Have Far Higher Emissions:

The February 2014 draft reduces EPA's estimate of total emissions from gas production. Yet several recent published studies based on regional atmospheric methane measurement indicate that estimates EPA proposes to lower were already too low.

We briefly summarize these atmospheric studies here. The first group of studies looked at particular regions. Two studies led by researchers with the National Ocean and Atmospheric Administration (NOAA) Earth System Research Laboratory that have directly measured methane in the atmosphere in other regions have estimated high leak rates. The first of these studies explains that by monitoring methane, propane, benzene, and other volatile organic compounds in the air around oil and gas fields, the authors can estimate oil and gas production's contributions to these pollutant levels. According to the study authors, their "analysis suggests that the emissions of the species we measure are most likely underestimated in [1990-2010] inventories," perhaps by as much as a factor of two, which would imply a leak rate of about

4.8% of production. A second announced NOAA study suggests that leak rates in the Uinta may be as high as 9%. Additionally, we note that a California study identified a 17% leak rate for oil and gas (presumably primarily oil) operations in the Los Angeles basin.

The second group of studies, released in the last four months, looks at nationwide gas production emissions and specifically criticizes the prior inventory as underestimating GHG emissions from gas production. In December of 2013, a paper published by Scot M. Miller et al. in the Proceedings of the Natural Academy of Sciences reviewed atmospheric measurements of methane and concluded that "The US EPA recently decreased its CH4 emissions factors for fossil fuel extraction and processing by 25–30% (for 1990–2011), but we find that CH4 data from across North America instead indicate the need for a larger adjustment of the opposite sign." In other words, rather than reducing the estimated leak rate from 2.4% to something approaching 1.5%, EPA should have increased its estimate to at least 3%. In February, a paper published in Science similarly concluded that the then current inventory underestimated methane emissions from gas production—indicating that the February 2014 draft is a change in the wrong direction.

Sierra Club has not identified the likely reason for the discrepancy between these "top down" assessments incorporating atmospheric measurements and EPA's "bottom up" estimate based on individual components, practices, and emission factors. Assuming the atmospheric studies to be correct, factors contributing to this discrepancy may include underestimation of the number of wells, a system wide underestimation of per component emission factors, drastic underestimation of emissions from particular sources (perhaps pneumatics or liquids unloading), or there may be some other cause. Although we are unable to recommend a particular correction to the inventory fully reconcile the inventory with these studies, we strongly encourage EPA to devote attention to this issue.

Comment: The "UT Austin-EDF" Study Further Indicates That The Inventory Underestimates Gas Systems Emissions:

The 2014 draft acknowledges a study by David Allen, of University of Texas, Austin, et al. and sponsored by the Environmental Defense Fund (EDF) as a source of additional information regarding gas and petroleum system emissions; the draft generally refers to this work as the "UT Austin EDF study." This study also generally indicates that the inventory underestimates emissions from gas systems. For the wells and completions included in this study, observed emissions were similar to average gas system emissions implied by the 2013 GHG inventory. However, the UT Austin EDF study found much higher utilization of reduced emission completions than are contemplated by the EPA inventories, resulting in drastically lower emissions from that particular slice of the lifecycle. These reduced completion emissions were offset, however, by increases from other components, such as pneumatics, in excess of those assumed by the inventory. These observed high rates of emissions from activities other than completions should be expected to apply industry wide, indicating that 2013 inventory underestimated these emissions. More generally, the UT Austin-EDF study should be assumed to represent the top end of performers, insofar as the wells included were from large industry players who opted in to the study and who had notice that measurements would be taken. EPA should look critically at emission estimates that would indicate that the industry as a whole performs better than the subset of players and wells included in the UT Austin-EDF study.

Comment: The Inventory Likely Underestimates Emissions from Pneumatic Devices:

As noted above, the UT Austin-EDF study indicates that the inventory significantly underestimates emissions from pneumatic devices. Until individual pneumatic devices are reported pursuant to Subpart W, EPA should adopt an approach such as the one recommended by EDF in their separate comment on the February 2014 draft.

Comment: Petroleum Systems Estimates Must Account for Unconventional Production:

There can be no disputing that hydraulic fracturing has changed the face of American petroleum production and has been employed in a large percentage of petroleum wells for a number of years. FracFocus, the national hydraulic fracturing chemical registry managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission, includes records from 12,056 oil wells that were hydraulically fractured in 2012. Yet the 2014 draft of the inventory estimates petroleum system emissions only using emission factors for conventional production. As explained in comments submitted separately by the Environmental Defense Fund, many of the tools EPA proposes to use to estimate gas systems emissions can also be applied to petroleum systems. Although these tools are imperfect, they can provide a much more accurate estimate of emissions than the draft inventory's inaccurate assumption that hydraulic fracturing is not used in petroleum wells.

Comment: EPA Uses an Outdated, and Far Too Low, Estimate of Methane's Global Warming Potential:

The inventory discusses methane's global warming potential (GWP) on the 100 year timeframe, and estimates this potential as 21. EPA explains that it uses this value pursuant to UNFCCC reporting obligations. Id. Yet as EPA recognizes, this value does not represent the best available science. As an interim measure, EPA provides an annex with many charts explaining the impact of using the 2007 Intergovernmental Panel on Climate Change (IPCC) 100 year methane GWP estimate of 25, Annex 6.1, but even that estimate has been superseded in the intervening seven years of research. Most importantly, the IPCC's Fifth Assessment Report estimates an aggregate 100-year methane GWP of 34, and an even higher estimate of 36 for methane emitted from fossil sources.

EPA must therefore take available steps to encourage this reporting obligation to be updated to reflect the best available science. These steps include including informing other federal entities participating in negotiation of these agreements of the importance of using recent science. As an interim measure, EPA should present an annex using the methane GWP data from the IPCC AR5 report, as the draft inventory does for the IPCC AR4 data.

Supplemental Material Received

Appendix A
Environmental Defense Fund White Paper on Methane Emissions from Co-Producing Well Completions

Appendix B
Energy Innovation Missing Methane Issue Brief

Appendix C
Damascus Citizens for Sustainability Extended Report on a Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan, New York City, New York

Appendix D
Damascus Citizens for Sustainability citing Phillips et al. 2012

Appendix E
Damascus Citizens for Sustainability citing Pieschl et al. 2013

Appendix F
Damascus Citizens for Sustainability Report on a Survey of Ground-Level Ambient Methane Levels in the Vicinity of Wyalusing, Bradford County, Pennsylvania

Appendix G
Damascus Citizens for Sustainability citing Report to the Clean Air Council of the June 8, 2012, on Field Inspection and Methane Sampling Survey

Appendix H
Damascus Citizens for Sustainability citing Tollefson 2013

Appendix I
Damascus Citizens for Sustainability citing Tollefson 2012

Appendix J
Damascus Citizens for Sustainability citing Miller et. al 2013

Appendix A

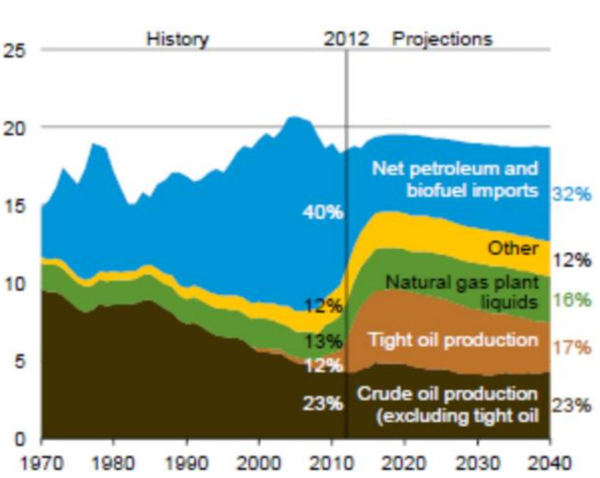
CO-PRODUCING WELLS AS A MAJOR SOURCE OF METHANE EMISSIONS: A REVIEW OF RECENT ANALYSES

PREPARED BY ENVIRONMENTAL DEFENSE FUND
MARCH 2014

The Environmental Protection Agency's ("EPA's") New Source Performance Standards ("NSPS") for the oil and natural gas sector require that hydraulically fractured natural gas wells reduce their completion emissions using either reduced emission completions ("RECs") or flaring.[1] EPA defines a "gas well" or "natural gas well" as "an onshore well drilled principally for production of natural gas"[2] and, depending on how this definition is interpreted, a number of wells that co-produce oil (or other liquids) and natural gas ("co-producing wells") may not need to control their emissions under the REC requirements in the NSPS.

Many completions of these co-producing wells, however, produce substantial pollution that can be cost-effectively mitigated using the same clean air measures that have effectively reduced emissions from hydraulically fractured gas wells. Extending clean air protections to co-producing wells is vital given recent trends within the oil and gas industry. Over the last two years, rising oil prices and low natural gas prices have caused new drilling activity to increasingly shift to shale formations rich in oil and condensates. Reflecting this trend, the U.S. Energy Information's ("EIA's") most recent Annual Energy Outlook predicts that domestic oil production will grow significantly through 2020, driven primarily by increases in tight oil production (see Figure 1).

Figure 1. US Petroleum and Other Liquids Supply, 1970-2040 (EIA)



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[1] With limited exceptions, all fractured and refractured natural gas wells will be required to use RECs as of January 1, 2015. 77 Fed. Reg. 49,490, 49,497 (Aug. 16, 2012).

[2] 40 C.F.R. § 60.5430.

This analysis synthesizes available information on per-completion emissions factors, the cost-effectiveness of mitigating those emissions using RECs or high-efficiency flaring, and, where possible, the total amount of methane that would be reduced by deploying these completion protections at co-producing wells. Table 1 synthesizes data from the following sources:

- A February, 2014 Stanford/Novim Study in the journal Science entitled "Methane Leakage from North American Natural Gas Systems;" ("Stanford/Novim Analysis")[3]
- ICF International's Report from March, 2014 entitled "Economic Analysis of Methane Emissions Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries;" ("ICF Report")[4]
- A 2013 analysis in the Proceedings of the National Academy of Sciences led by the University of Texas entitled "Measurements of methane emissions at natural gas production sites in the United States;"[5] ("UT Study")
- EDF's analysis of the oil and natural gas portion of EPA's Greenhouse Gas Reporting Program ("EDF Subpart W Analysis");[6] and
- An analysis completed by EDF and Stratus Consulting of well completion reports in the Bakken, Eagle Ford, and Wattenberg field ("EDF/Stratus Analysis").

These sources all indicate that co-producing well completions are a substantial source of methane emissions, with total estimated emissions much larger than the figure reported in EPA's official inventory of greenhouse gas emissions. EPA's current emission factor for co-producing wells derives from a 1996 study of conventional oil wells, and very likely underestimates emissions from the hydraulic fracturing techniques that are prevalent today.

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[3] A.R. Brandt et al., Methane Leaks from North American Natural Gas Systems, 343 SCIENCE 733 (Feb. 14, 2014), available at http://www.novim.org/images/pdf/ScienceMethane.02.14.14.pdf.

[4] The report is available at http://www.edf.org/sites/default/files/methane_cost_curve_report.pdf.

[5] David T. Allen et al., Measurements of methane emissions at natural gas production sites in the United States, PNAS Early Edition (2013), available at www.pnas.org/cgi/doi/10.1073/pnas.1304880110.

[6] EDF, Comments on "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012" (included in the supplemental information for this analysis).

TABLE 1: Summary of Co-producing Emissions, Cost-Effectiveness, and Mitigation Potential

Data Sources	Potential Emission Factor (MT CH_4)	National Emissions Estimates*** (MT CH_4)	REC Cost Effectiveness ($/MT CH_4)		Flaring Cost Effectiveness ($/MT CH_4)	Methane Mitigation Potential (MT CH_4)
			without savings	with savings		
Stanford/ Novim Analysis*	40.2[7]	120,000****	778		92	114,000
ICF Report	6.6**	96,000	n/a	n/a	96.57	94,000
UT Study*	193.5		153.8	-132.7[8]	19.19	n/a
EDF Subpart W Analysis	21.8	163,000	1,435		170	140,000
EDF/Stratus Analysis	15.7	247,000	3,578	3,314	424	235,000

*Analysis includes potential emissions factor only. Cost-effectiveness and mitigation potential derived using common assumptions described below.
** This EF includes both vented emissions controlled emissions so is not a true potential emissions factor.
*** Estimates provided by the authors of each individual study.
**** This estimate only reflects emissions from three major production basins, and therefore understates total national emissions.

The remainder of this white paper provides additional information on the development of an emission factor for co-producing wells, the cost-effectiveness of mitigating these emissions, and overall methane mitigation potentials.

Potential Emission Factor

The above-described analyses determine potential emissions factors for co-producing well completions using several different methods, including direct measurement, analysis of Subpart W data, and analysis of initial oil and gas production. All of these analyses find potential emissions are significantly greater than the emissions factor for oil well completions currently in EPA's annual greenhouse gas inventory (0.0141 tons of methane per completion). Given that EPA's current emissions factor is dated and was based on emissions from completions of conventional, non-hydraulically fractured wells, the more recent studies described below suggest that the official inventory is likely underestimating the extensive methane emissions from co-producing well completions. Moreover, neither the current NSPS

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[7] Weighted average of emission factors for wells in the Bakken, Eagle Ford, and Permian Basins.

[8] On average, these wells would achieve net savings of $25,630 by selling gas recovered during completions, assuming $4/Mcf.

nor the regulations of most states require control of completion emissions from co-producing wells.[9]

UT Study. The UT Study measured various large sources of methane in the production sector, including 27 well completions in various geographic areas across the country. Six of the measured completions were at co-producing wells that produced significant amounts of hydrocarbon liquids,[10] and, for each of these completions, researchers directly measured potential and actual methane emissions. Actual completion emissions from these co-producing wells ranged from 1.7 to 5.0 metric tons ("MT") CH_4, though all of the wells controlled completion flowback emissions with either flaring or a combination of RECs and flaring. The UT study estimated potential emissions as the total volume of gas vented, flared, and sent to sales from initiation of flowback until the reported completion end time. The potential emissions from these wells, which would be more indicative of uncontrolled completions, ranged from 81.9 to 414.4 MT CH_4, with an average value of 193.5 MT of CH_4/completion.[11]

Table 1. Measured and potential emissions of co-producing wells from Allen, et al. (2013)

Completion Event	Emission Controls	Measured Emissions (scf CH_4)	Potential Emissions (scf CH_4)	Measured Emissions (MT CH_4)	Potential Emissions (MT CH_4)
GC-1	Flaring	105,000	5,005,000	2.0	96.4
GC-2	Flaring	90,000	4,250,000	1.7	81.9
GC-3	REC & Flaring	260,000	21,500,000	5.0	414.1
GC-4	REC & Flaring	180,000	13,000,000	3.5	250.4
GC-6	Flaring	247,000	12,200,000	4.8	235.0
GC-7	Flaring	90,000	4,320,000	1.7	83.2
Average		162,000	10,030,000	3.1	193.5

Subpart W Analyses. EDF also evaluated completion data from 2011 and 2012 that was reported to EPA under its greenhouse gas reporting rule for oil and gas systems (known as "Subpart W").[12] Subpart W does not require reporting of oil well completion and workover

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[9] Notably, Colorado does require that co-producing wells perform reduced emission completions. Co. Oil & Gas Conserv. Comm'n ("COGCC") Rule 805(b)(3)(A).

[10] David T. Allen et al., Measurements of methane emissions at natural gas production sites in the United States, PNAS Early Edition (2013), available at www.pnas.org/cgi/doi/10.1073/pnas.1304880110. See also EDF, Analysis of Co-Producing Well Completions (updated Mar. 2013) (included in the supplemental information for this analysis).

[11] EDF, Analysis of Co-Producing Well Completions (Dec. 2013). The underlying study analyzed a total of 26 well completions.

[12] EDF, Comments on "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012" (included in the supplemental information for this analysis).

emissions. Nonetheless, in 2011 and 2012 there were 1,754 reports of completions and workovers from wells in formations classified under Subpart W as "oil formations." EDF performed a separate analysis of DI Desktop data to assess if these completions were actually oil wells.[13] In approximately 75% of the counties from which these completion reports came, over half of the wells with first production in 2011 & 2012 were oil wells. Using the same approach that EPA used to estimate emission factors for completions from the entire GHGRP dataset, EDF has derived emission factors for this subset of wells located in oil formations (Table 3). The average emission factor for all oil formation completion and workovers is 6.2 MT CH_4/event, or more than 400 times higher than the current oil well completion emission factor. EDF also developed separate emission factors for each combination of emission controls reported under Subpart W: uncontrolled ("vented") completions, completions controlled with a flare, completions controlled with a REC, and completions controlled with both flares and REC. The emission factors for the four categories range from 3.1 MT CH_4/event for completions with REC to 21.8 MT CH_4/event for vented completions.

The ICF Report also uses Subpart W data to develop an emission factor for hydraulically fractured oil wells. From this data, the Report develops an emissions factor of 344,000 scf CH_4/completion or 6.6 MT CH_4/completion, which is an average value including both controlled and uncontrolled completions.

Table 3. Oil well completion and workover emission factors developed from 2011 & 2012 GHGRP Subpart W oil formation type sub-basins using the same method as EPA for developing the natural gas completion and workover emission factors

Category	Completions (# events)	Workovers (# events)	Completions & Workovers (# events)	Completions EF (MT CH_4/event)	Workovers EF (MT CH_4/event)	Completion & Workover EF (MT CH_4/event)
Vent	320	147	467	21.8	7.6	17.3
Flare	221	66	287	3.7	2.5	3.4
REC	186	0	186	3.1	N/A	3.1
REC+Flare	17	0	17	11.7	N/A	11.7
Ambiguous	708	89	797	1.5	0.0	1.3
All events	1,452	302	1,754	6.6	4.2	6.2

Initial Production Analyses. The Stanford/Novim Analysis evaluated 2,969 well completions in the Bakken, Eagle Ford, and Permian basins for 2011 using the DrillingInfo HPDI Database.[14] The analysis estimated potential emissions from these tight oil wells by converting

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[13] Data obtained from DrillingInfo, DI Desktop, http://info.drillinginfo.com/products/di-desktop/.

[14] A.R. Brandt et al., Methane Leaks from North American Natural Gas Systems, 343 SCIENCE 733 (Feb. 14, 2014), available at http://www.novim.org/images/pdf/ScienceMethane.02.14.14.pdf. The relevant data is contained in the supporting documentation for the study (http://www.sciencemag.org/content/suppl/2014/02/12/343.6172.733.DC1/Brandt.SM.datafile.xlsx).

peak gas production to a daily initial production rate. It then assumed that production during flowback increased linearly with time for 9 days prior to initial production and all such methane emissions were vented, or understood differently, that completion emissions correspond to 4.5 days of initial gas production.[15] Using this methodology, the analysis determined potential emissions factors for the Bakken (31.1 MT CH_4/completion), Eagle Ford (90.9 MT CH_4/completion), and Permian (31.2 MT CH_4/completion) Basins.

The EDF/Stratus analysis takes a similar approach, using initial production values to understand potential completion emissions at co-producing wells. Stratus Consulting initially performed an analysis of 100 well completions in the Bakken, assuming a 7 to 10 day completion event with gas production increasing from zero to the initial production value in a non-linear fashion over the course of the completion. Accordingly, Stratus assumed that total gas production over the 7-10 day completion event would equal 3 average days of gas production.[16] As with the Stanford/Novim analysis, Stratus assumed all of this gas was vented.

EDF subsequently extended this analysis to approximately 9,500 wells in the Bakken, Eagle Ford, and Wattenberg fields.[17] Only oil wells were analyzed for the Eagle Ford and Wattenberg fields; North Dakota does not distinguish between oil and gas wells so all Bakken wells were assumed to be oil wells. Across all wells, the analysis found an average potential emissions factor of 15.7 MT CH_4/completions with averages of 18.0, 24.7, and 9.5 MT CH_4/completion in the Bakken, Eagle Ford, and Wattenberg respectively.

Cost Effectiveness

Other than the ICF Report, none of the above non-EDF analyses calculated the cost-effectiveness of controlling completion emissions using RECs or high-efficiency flaring. Accordingly, we applied consistent cost assumptions to all of the analyses above, except the ICF Report. For RECs, we assumed 95% control efficiency and used EPA's cost of performing a reduced emission completion ($29,713)[18] to calculate cost-effectiveness. Across all studies, we calculated a REC cost-effectiveness without a credit for captured gas ranging from $154 - $3,578/MT CH_4 reduced. Using production data from approximately 9,500 wells in the Bakken, Eagle Ford, and Wattenberg fields, we calculated a REC cost-effectiveness with credit for gas

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[15] This methodology is set forth in Francis O'Sullivan & Sergey Paltsev, Shale gas production: potential versus actual greenhouse gas emissions, ENVTL. RES. LETTERS 7(4):044030 (Nov. 26, 2012).

[16] Memorandum from Leland Deck, Stratus Consulting, to Peter Zalzal and Vickie Patton, Environmental Defense Fund, re: Methods Memo on VOC Cost-Effectiveness in Controlling Bakken Shale Combined Oil and Gas Wells During Well Completion (Mar. 30, 2012) (included in the supplemental information for this analysis).

[17] EDF, Spreadsheets analyzing Bakken, Eagle Ford and Wattenberg wells (included in the supplemental information for this analysis).

[18] EPA, Oil and Natural Gas Sector: Standards of Performance for Crude Oil and Natural Gas Production, Transmission, and Distribution, Background Technical Support Document for Proposed Standards (July 2011), available at http://www.epa.gov/airquality/oilandgas/pdfs/20110728tsd.pdf.

capture. With a credit for gas savings (based on an assumed gas price of $4.00/Mcf), we calculated a median cost-effectiveness of $3,314/MT CH_4 reduced and also calculated cost-effectiveness for the top 25% and top 10% of wells, as shown in the table below.

Table 4. EDF / Stratus REC Cost-Effectiveness for Median and Top 25 and 10 Percent of Wells

Percentile	REC Cost Effectiveness with gas capture credit ($/MT CH4)	Mitigation Potential (MT CH4)	Mitigation Potential (% of total)
10%	$544	60,643	40.9
25%	$1,266	97,430	65.7
50%	$3,314	126,508	85.3

To calculate flaring cost effectiveness, we assumed 95% destruction and removal efficiency ("DRE") and multiplied this by the emission factor to get flaring emission reductions. We then divided the EPA cost estimate of flaring completion emissions from a well ($3,523) by the flaring emission reductions for each of the analyses.[19] Across all studies (excluding the ICF Report) we calculated a flaring cost-effectiveness ranging from $19 - $424/MT CH_4 reduced.

The ICF Report includes its own cost assumptions about performing high-efficiency flaring, which are substantially higher than those in EPA's NSPS. ICF assumes flaring has a 98 percent control efficiency and a capital cost of $50,000, with an additional $6,000 in fuel costs for ignition. ICF estimates the cost-effectiveness of flaring to be $1.86/Mcf of methane ($97/MT CH_4) for completion gas. The ICF report did not examine the cost-effectiveness of RECs for co-producing wells.

Mitigation Potential

Determining inventory-wide mitigation potential requires scaling up emissions nationally and then applying percentage reductions associated with mitigation technologies. The Stanford/Novim Analysis, the ICF Report, the EDF Subpart W Analysis, and the EDF/Stratus Analysis all provide national estimates of emissions from co-producing wells, which we describe in greater detail below. The UT Study does not scale these specific emissions nationally and we have not provided a separate scale up of those emissions here.

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[19] Id.

- Stanford/Novim Analysis. The Stanford/Novim analysis found that co-producing well completions accounted for approximately 120,000 MT CH_4 in 2011.[20] The analysis assumed all emissions were vented and multiplied emissions factors in the Bakken, Eagle Ford, and Permian Basins by the total number of completions in those basins. Because the 120,000 MT CH_4 figure includes only emissions from these three basins, it is not a true national figure.

- ICF Report. ICF used its emissions factor of 344,000 scf CH_4/completion (6.6 MT CH_4/completion) from Subpart W along with the most recent API Quarterly Completions Report showing 15,382 hydraulically fractured oil well completions for 2011. Using these values, ICF calculated completion emissions of 5 Bcf CH_4 or 96,000 MT CH_4.

- EDF Subpart W Analysis. EDF applied emissions factors we calculated from Subpart W to the 2012 Draft GHG Inventory activity data of 15,753 oil well completions.[21] This resulted in emission estimates between 49,000 MT CH_4 (assuming all RECs) and 343,000 MT CH_4 (assuming all emissions vented), or 182,000 MT CH_4 if the use of emission controls among the 15,753 oil well completions is assumed to be distributed in the same way as the Subpart W dataset. Because some wells are already controlled, we assumed the national proportion of uncontrolled completions was 43%, the same as the Subpart W dataset, and applied the emission factor for vented completions. We use this 147,000 MT CH_4 value for purposes of determining mitigation potential.

- EDF/Stratus Analysis. The EDF/Stratus analysis did not isolate hydraulically fractured wells, but instead derived an average emission factor applicable to all co-producing well completions. Accordingly, EDF applied emissions factors we calculated using the Stratus methodology to EPA's 2012 Draft GHG Inventory activity data of 15,753 oil well completions for an emissions estimate of approximately 247,000 MT CH_4 annually.

Translating these national emissions estimates into mitigation potential requires applying control efficiencies. The ICF Report assumes flaring achieves 98% DRE, and accordingly suggests mitigating completion emissions from co-producing wells could achieve 94,000 MT CH_4 in annual reductions.

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[20] A.R. Brandt et al., Supplementary Materials for Methane Leaks from North American Natural Gas Systems 30, 343 SCIENCE 733 (Feb. 14, 2014), available at http://www.sciencemag.org/content/suppl/2014/02/12/343.6172.733.DC1/1247045.Brandt.SM.pdf.

[21] Although not all oil wells completions use hydraulic fracturing, FracFocus, the national hydraulic fracturing chemical registry managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission, includes records from 12,056 oil wells that were hydraulically fractured in 2012. Reporting to FracFocus is voluntary in many states, which implies that the actual number of hydraulically fractured oil wells is higher than 12,056. Accordingly, we have used the draft inventory activity data as a reasonable proxy for the total number of hydraulically fractured oil well completions.

The Stanford/Novim analysis does not calculate mitigation potential, and so, consistent with the two EDF analyses, we conservatively assume flaring or gas capture achieves a 95% control efficiency. Because both the Stanford/Novim analysis and EDF/Stratus analysis assume all emissions are vented, we apply the 95% control figure directly to total emissions estimates, resulting in annual mitigation potentials of 114,000 MT CH_4 and 228,000 MT CH_4 respectively. Because EDF's Subpart W analysis assumes some wells are already controlled, we apply the 95% control effectiveness only to the subset of emissions that are vented for an annual mitigation potential of 140,000 MT CH_4.

Conclusions

Although neither EPA regulations nor the regulations of most states require control of emissions from co-producing well completions, these emissions are a potentially significant source of methane and other harmful pollutants. Recent studies and analyses – drawing from a variety of data sources including field studies of well completions, Subpart W reports, and well completion databases – suggest that emissions from an uncontrolled co-producing well completion range from 15.7 MT of CH_4 to nearly 200 MT. At a national level, these emission factors suggest total co-producing well completion emissions between approximately 96,000 to 247,000 MT, comparable to emissions from natural gas well completions (209,000 MT CH_4 in the latest EPA annual inventory). Current control technologies for natural gas well completions – including RECs where gathering infrastructure is available, and high-efficiency flaring in other situations – can be readily applied to co-producing well completions. This white paper suggests that applying those technologies to co-producing well completions would yield emission reductions on the order of 94,000 to 228,000 MT per year, or 2.63 to 6.38 million MT CO_2-e (using 100-year GWP of 28).

Appendix B

ENERGY INNOVATION
POLICY & TECHNOLOGY, LLC

The Mystery of the Missing Methane

Advances in the scientific understanding of methane emissions highlight the need for improvements to the EPA emissions inventory

By Chris Busch

25 March 2014

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1. Summary

The U.S. Environmental Protection Agency (EPA) recently released a draft of its 1990-2012 greenhouse gas (GHG) emissions inventory. While the EPA is in many ways at the frontier of global best practice, the agency needs to take action to account for the accumulating evidence that the GHG inventory is omitting a significant fraction of methane emissions, the second most prevalent contributor to climate change. The new draft inventory estimates that emissions fell almost two percent in 2012 compared to 2011, and it revises downward previous estimates of methane emissions for the natural gas sector. For example, 2011 emissions are almost 10 percent lower in the 2014 draft inventory than they were in the 2013 inventory. These downward revisions are being made despite increasing scientific evidence that the EPA should be increasing its estimate of emissions.

Just one week before the draft inventory was released, the journal *Science* published a landmark study (Brandt et al., 2014) that concludes that the EPA inventory is undercounting emissions by a significant margin. The study brings together, for the first time, the full body of existing evidence on methane leakage. It estimates that there are 7-21 teragrams (Tg; 10^{12} grams) of methane missing from the EPA inventory and concludes that some of this methane is likely coming from the natural gas system. This quantity, 7-21 Tg, is equivalent to roughly 25–75 percent of the total methane emissions in the inventory and is two to four times the EPA's current estimate of methane emissions from the natural gas system.

The EPA needs to develop a plan to collect and analyze real-world data to narrow the uncertainty ranges and provide a better understanding of methane emissions, especially from the natural gas system. New technologies for detection and measurement of methane emissions can help the EPA achieve this goal. Additional resources should be dedicated to this objective.

2. Bottom-up vs. top-down studies of methane emissions

The EPA emission inventory relies on "bottom-up" studies of methane emissions. Bottom-up studies involve component-level sampling on the ground, at the source. The EPA uses the results from these studies to calculate emission factors for different activities that make up the natural gas system, including production, processing, transmission, and distribution. These emission factors—essentially, typical levels of emissions per unit output for different components of the system—are applied to natural gas production activities to calculate activity-specific emissions, and then are summed to estimate total system-wide emissions. As the EPA inventory for the natural gas system is constructed, uncontrolled emissions are first estimated using the process above (the "potential emissions"), then regulatory initiatives and voluntary information provided by companies are taken into account to produce estimated emissions.

Figure 1. Methane emissions are invisible to the naked eye

Methane emissions from this storage tank are visible not the naked eye but an infrared lens reveals their existence. Photo source: New York Times.

One of challenges with bottom-up studies is that they require the participation of landowners and natural gas companies. Researchers must obtain permission in order to enter a property and directly measure emissions, and have not found it easy to do this. There is some reason to believe that the producers that have voluntarily participated are the cleanest, lowest-emitting operators. This, in combination with the great heterogeneity in types of operations and geology across gas-bearing basins, means that it is difficult for bottom-up studies to collect data from a broad enough array of sources for the sampling to be representative.

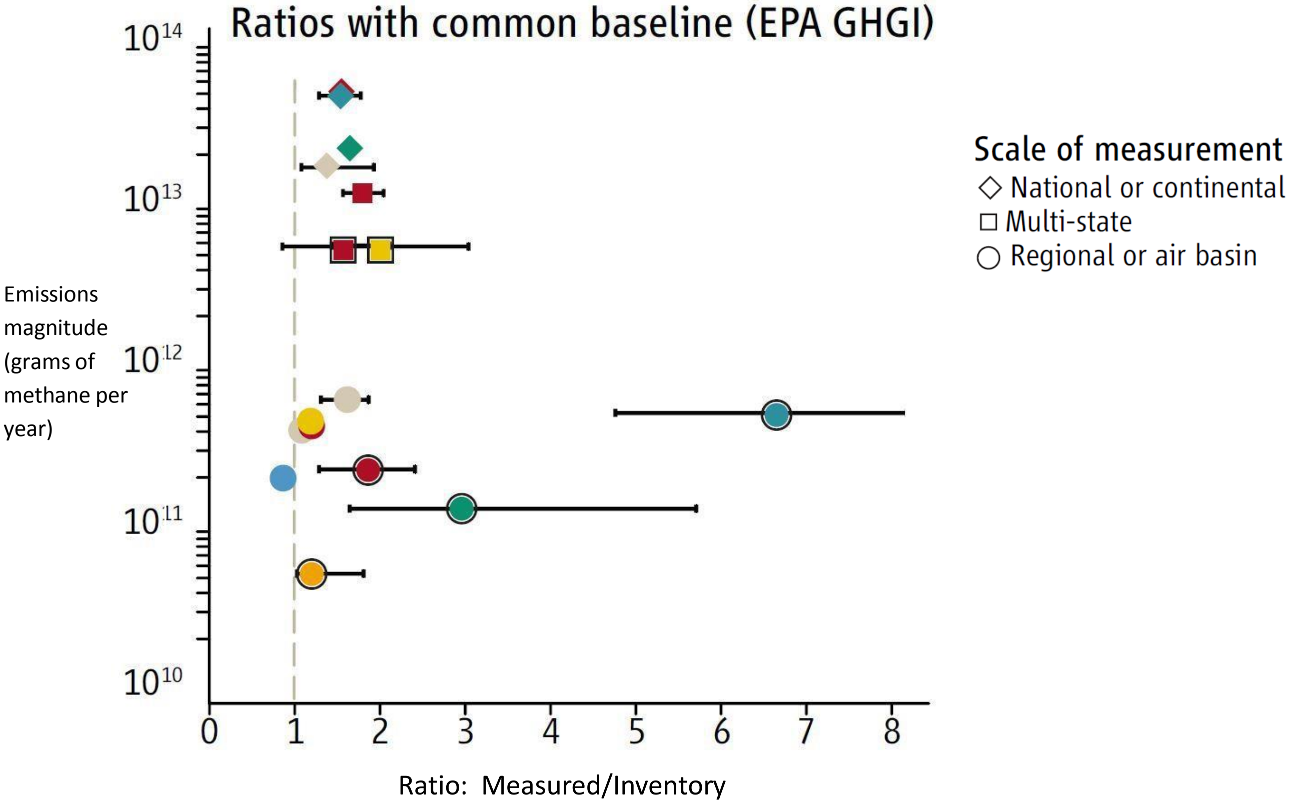
"Top-down" studies are a second, distinct approach for measuring methane emissions. These studies are based on atmospheric sampling from aircraft or tall towers. Top-down studies provide great accuracy with respect to the quantity of total emissions (though some uncertainty is introduced by wind-blown methane that might enter or exit the study area before being sampled). Traditionally, the weakness of top-down studies has been the difficulty of discerning the contribution of different sources the overall level observed level of methane. Many top-down studies have not even attempted to attribute the methane sampled in the atmosphere to particular sources on the ground. However, emerging techniques are making progress in allowing identification of likely sources for atmospherically sampled methane.

3. The missing methane

Brandt et al.’s paper is innovative in two ways. First, they provide a framework for comparison of past studies on methane emissions. In a feat of graphic creativity, Brandt et al. put all of the existing studies, bottom-up (denoted by triangles and dashes) and top-down (denoted by circles, squares, and diamonds), on a single chart. The result helps illuminate how these two threads in the literature relate to each other. Bottom-up studies measure facilities or components: the largest value found by any such study was around 10^9 g of methane emitted per year. In contrast, even the smallest of the top-down studies, which measured the Denver-Julesberg basin, reported over $4*10^{10}$ g of methane.

Brandt et al. also conduct a meta-analysis of national-scale, top-down studies of methane emissions. The authors develop a normalization procedure to make the multitude of studies comparable. The result indicates that the most likely range of actual methane emissions is 25–75 percent higher than the EPA inventory indicates. This range of possible emissions is illustrated in the inset panel for Brandt et al.’s principal graphic, which we reproduce as Figure 2. Note that for all of the studies that are national or continental in scale, observations all lie between 1.25 and 1.75—that is 125 percent and 175 percent of the EPA inventory.

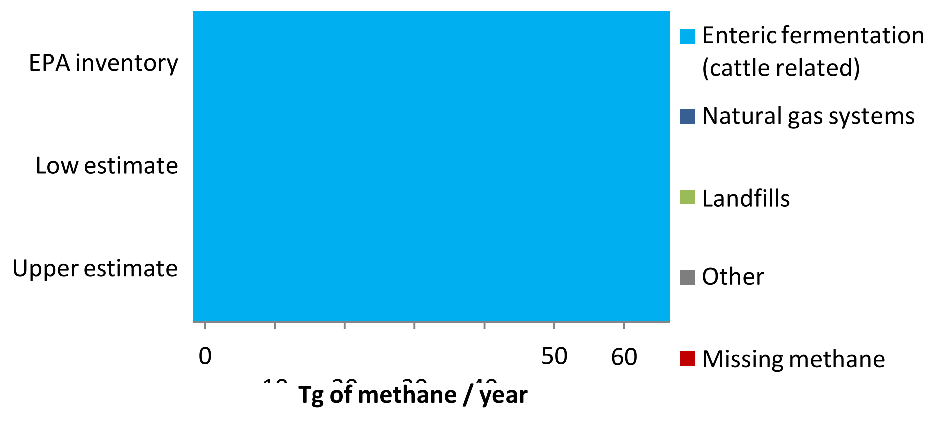
Figure 2. Normalized comparison of top-down studies in Brandt et al.



Source: Brandt et al., 2014

Figure 3 shows in red the lower and upper estimates (7- 21 Tg) of methane emissions that the EPA did not account for in their inventory, which we are referring to as missing methane. The missing methane is shown on top of the results from the EPA's latest inventory.

Figure 3. EPA methane inventory and estimates of missing methane



Because of the limited ability of top-down studies to trace methane back to specific ground-level sources, it is not possible to determine the origin of the missing methane with great certainty. Still, there is reason to believe that at least *some* of the missing methane is coming from the natural gas system, as there are downward structural biases in the inventory. For example, it would be reasonable to expect that facility operators who believe they may have above-average emissions would be hesitant to join voluntary studies. This may have a large impact on results, as there is accumulating evidence that "super emitters" – a small number of facilities with particularly large leaks – could be a majority or a large fraction of overall emissions. Another downward structural bias is the EPA's choice to reduce the emissions estimated through the bottom-up procedure based on industry assertions that they have taken voluntary actions above and beyond those required by regulations.

The large range of uncertainty remaining about the rate of emissions in the natural gas system is an indicator of the complexity of the situation. The natural gas system is large, complex and heterogeneous, in both engineering and geologic terms. Each natural gas-bearing basin is unique, and there is great variation in how producers operate. Methane emissions come not only from wells producing natural gas, but also from those mainly producing oil. Indeed, 20 percent of the nation's gas is "associated gas" produced at oil wells. Oil wells have different emissions characteristics from wells designed to extract primarily natural gas. The intermingling of the oil and natural gas systems also introduces the question of how to attribute methane emissions. Some of the methane emissions from the petroleum system should be attributed to natural gas, but determining the appropriate fraction is challenging.

4. Computational extensions

The Brandt et al. paper concludes that some of the missing methane is likely coming from the natural gas system. It explores the specific possible sources of methane from the natural gas system beyond the EPA estimates. In the supporting materials for the article, the authors develop what they call a worst-case scenario for emissions from the natural gas system that considers the notion that all of the missing methane is from natural gas. Under such a scenario, if 7-21 Tg of extra methane was being emitted from the natural gas system, that would imply emission rates two to four times higher than the EPA inventory estimate.

While concluding that some of the missing methane almost certainly originates from the natural gas system, the Brandt et al. paper also emphasizes the continued lack of certainty regarding the extent that natural gas emissions are underestimated. To emphasize this uncertainty, the authors consciously chose to refrain from translating missing methane into emission rates. We also find it useful to illustrate the potential magnitude of the problem through some further computation, including implied emission rates for the natural gas system at different levels of missing methane.

Here, we develop four scenarios, translating the missing methane into an emission rate of methane from the natural gas system. The emission rate is calculated by adding a portion of the missing methane (varying by scenario) to the methane emissions assigned to the natural gas industry in the EPA's inventory, then dividing that value by the sum of natural gas production plus total methane emission in that scenario. We also specify the ratio of each scenario's methane emissions attributed to natural gas systems to the corresponding value from the EPA inventory. The scenarios are shown in Table 1.

Table 1. Emission scenarios

Scenario	Implied missing methane from natural gas systems	Ratio of scenario to EPA natural gas system emission	Implied natural gas system emission rate
1.	1.8 Tg	1.25	1.75%
2.	3.5 Tg	1.5	2.1%
3.	7 Tg	2	2.8%
4.	14 Tg	3	4.2%

We chose these scenarios to provide the broadest range of what seems possible in light of the work by Brandt et al. The paper explicitly says that it is not likely that the 21 Tg of methane all comes from natural gas, so that total amount is not considered. The upper bound analyzed is 14 Tg extra from natural gas systems. At the low end of the range of scenarios, we analyze 1.8 Tg of extra methane coming from the natural gas system. This would be the case if, for example, the natural gas system is responsible for 25 percent of the lowest estimate of missing methane. Additionally, we consider two intermediate scenarios, under which 3.5 and 7 Tg of missing methane due to natural gas systems.

Next, we convert the methane leakage to carbon dioxide equivalent, which we use to compute an equivalency in coal plants. Coal plants comparisons are based on annual emissions using 2012 data for a generator of average efficiency, capacity factor and size for the U.S. fleet (a 543-megawatt generator operating at 85 percent capacity with a heat rate of 10,444 Btu per kilowatt-hour, from the Energy Information Administration 2013).

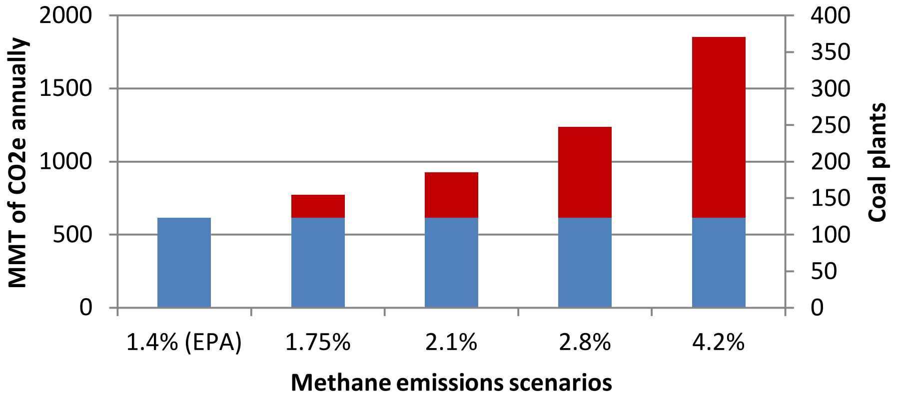
We use Global Warming Potential (GWP) factors to perform the conversion to CO_2 equivalent. GWP factors represent the relative contribution to global warming from GHGs other than carbon dioxide, which each have different atmospheric residence times and abilities to trap heat. All GHGs are defined in relation to carbon dioxide, the most prevalent GHG, which is assigned a GWP of one for all time periods.

Methane has an especially pronounced effect in the initial years and decades after it is released. Unlike carbon dioxide, which can continue to drive warming for hundreds or thousands of years after it is emitted, methane has an atmospheric residence time of approximately 12 years. However, while it is in the atmosphere, methane is a very potent greenhouse gas. Moreover, atmospheric chemistry transforms methane into carbon dioxide over time. The most recent Intergovernmental Panel on Climate Change (IPCC) reports GWP factors for methane of 34 over 100 years and 86 over 20 years, an increase since the prior IPCC report that reflects improved scientific understanding.

In the past, when climate change seemed like a distant problem, using 100-year GWP values was an accepted convention. The EPA inventory still refers to carbon dioxide equivalent without any reference to the timeframe with the expectation that readers will assume the numbers are on a 100-year scale. Today, with evidence of damages from climate change accumulating, there is increasing attention to near term climate disruptions. Put differently, the value of short-term climate mitigation benefits has been getting more attention from policy-makers. While carbon dioxide emissions will largely determine the extent of global warming in the long run (Harvey et al., 2013), reducing emissions of gases like methane will reduce short-run climate damages and can be used strategically to reduce peak warming (National Research Council 2011). Methane also contributes to the formation of ground-level ozone, so there are local air quality benefits to emission reductions.

This issue brief presents comparisons over both shorter and longer term time periods (20-year and 100-year GWPs). Figure 4 depicts the 20-year values in carbon dioxide equivalent (CO2e) and the comparable number of average coal plants for each of the leakage scenarios detailed in Table 1.

Figure 4. Natural gas sector methane emissions scenarios using 20-year GWP



The first bar represents the level of methane emissions from the natural gas sector in the EPA inventory. An emissions rate of 1.4 percent implies emissions equivalent to 124 coal plants using 20-year GWP. A 1.8 percent emissions rate would imply emissions with a carbon dioxide equivalency equal to 31 additional coal plants beyond the basic inventory estimate, for a total of 155. Leakage of 4.2 percent would imply additional emissions with a carbon dioxide equivalency equal to 249 more coal plants, for a total of 373.

Figure 5. Natural gas sector methane emissions scenarios using 100-year GWP

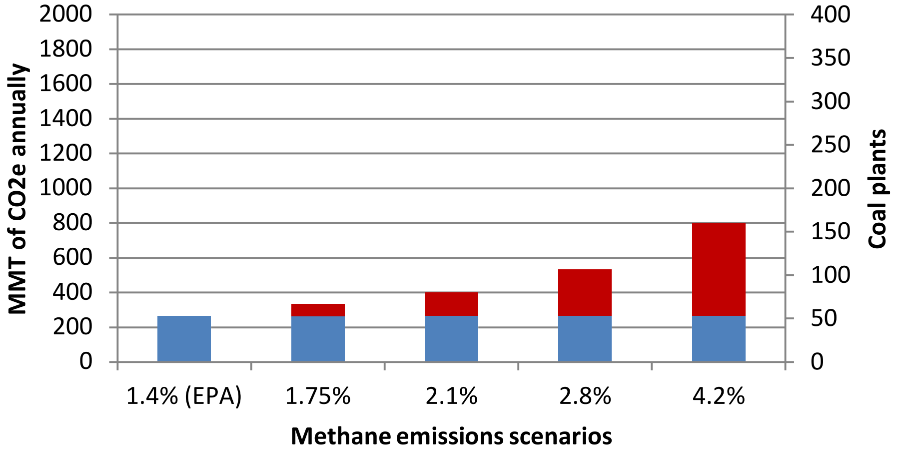


Figure 5 shows that, using 100-year GWP factors, the EPA estimate of methane leakage, 1.4 percent, has a carbon dioxide equivalency equal to 53 coal plants. A leakage rate of 1.8 percent would imply additional emissions with a carbon dioxide equivalency equal to 13 additional coal plants, for a total of

66. Doubling EPA's leakage rate to 2.8 percent results in an additional 53 coal plants, for a total of 106. A tripling of emissions to 4.2 percent would imply additional emissions with a carbon dioxide equivalency equal to 107 more coal plants, for a total of 160.

5. Implications for emissions impacts of electricity from natural gas

Proponents of natural gas have pointed to the lower carbon dioxide pollution emitted from the smokestacks of natural gas-fired electricity generators. Natural gas plants have smokestack emissions that are roughly half those of coal-fired power plants. Yet, methane emissions from the natural gas system significantly reduce this smokestack advantage. One of the reasons it is important to characterize methane emissions from the natural gas system more accurately is to provide a more accurate picture of the environmental impacts of electricity produced with natural gas. (It is worth noting that electricity generation accounted for 39 percent of natural gas consumption in 2012. Therefore, it is only appropriate to attribute that same fraction of the missing methane to electricity generated from natural gas.)

Based on the new understanding of the likely range of methane leakage provided by Brant et al., it seems very likely that substituting natural gas for coal-combustion to produce electricity actually exacerbates climate change over the short run, i.e. 20 years, and lowers greenhouse gas emissions over the long run, i.e. 100 years, (Alvarez et al. 2012). Being somewhat better than coal over a 100-year time horizon is hardly a sufficient condition to conclude that natural gas can serve as the low-carbon bridge to a clean energy future, as it is often called. In a U.S. context, it has been suggested that natural gas use will have to peak by 2030 for the Obama administration's climate goal to be achieved (Banks and Taraska 2013). From a global perspective, even those who extoll the virtues of natural gas have found that if global concentrations of carbon dioxide are to remain below 450 part per million - the level that scientists are targeting to limit the risks of dangerous climate change - then the time is very short for natural gas to serve as a useful bridge fuel (Levi 2012).

6. Conclusion

The EPA should take steps to address clear evidence that its inventory of GHG emissions is undercounting methane. In the short run, as part of finalizing the 2014 inventory, the agency should make the case for a significant effort to improve the inventory of emissions from the natural gas sector. In the longer run, the agency should develop a plan for integrating top-down data as well as new technologies that operate at ground level that can assist in leak detection and measurement. The federal government should be placing more emphasis in and devoting more resources to this effort.

Brandt et al.'s work illustrates the value of top-down measurements to provide evidence of overall emission levels over large areas. The EPA should move to collect airborne measurements into its GHG inventories. By conducting measurement campaigns, EPA will be able to obtain atmospheric data that is more comprehensive across space and time. This will enable the agency to identify aggregate emissions levels with much greater accuracy and will help to improve confidence intervals. Current confidence intervals are much too small in light of uncertainty about the true value.

Emerging technologies can link emissions back to sources, enabling the EPA to conduct an effective ground-level measurement campaign. Infrared cameras are effective at locating leaks, and their use has been required under a recently approved Colorado regulation. Low cost stationary detectors are also under development. The newest detectors can locate leaks and estimate their magnitude from a distance, which reduces the challenge of acquiring property owner permission that bedevils direct on-site measurement.

The current oil and gas boom has been unleashed by a wave of technological innovation (directional drilling, hydraulic fracturing, and other emerging techniques, like "acidizing"). Governments need to keep pace with faster innovation on the regulatory side. New monitoring technologies are an opportunity for greater accuracy, and the EPA should move quickly to use these technologies to transform government monitoring of emissions. Better monitoring of emissions will help the EPA solve the mystery of the missing methane and provide the best objective guidance to policymakers, regulators, and society.

Acknowledgments

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References

Alvarez, Ramon, S.W. Pacala, J.J. Winebrake, W.L. Chameides, and S.P. Hamburge. 2012. "Greater focus needed on methane leakage from natural gas infrastructure," *Proceedings of the National Academy of Sciences* 109(17): 6435-6440.

Banks, Darryl and Gwynne Taraska. 2013. *U.S. Natural-Gas Use Must Peak by 2030.* Center for American Progress: Washington, DC.

Brandt, A.R., G.A. Heath, E.A. Kort, F. O'Sullivan, G. Petron, S.M. Joraan, P. Tans, J. Wilcox, A.M. Gopstein, D. Arent, S. Wofsy, N.J. Brown, R. Bradley, G.D. Stuckey, D. Eardley, R. Harriss. 2014. "Methane Leaks from North American Natural Gas Systems," *Science* 343: 733-735.

Energy Information Administration (US Department of Energy). 2013. *Electric Power Annual*.

Harvey, Hal, Franklin Orr, and Clara Vondrich. 2013. "A Trillion Tons," Daedalus 142(1): 8-25.

Levi, Michael. 2013. "Climate consequences of natural gas as a bridge fuel," *Climatic Change* 118 (3-4): 609-623.

National Research Council. 2011. *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millenia.* The National Academies Press: Washington, DC.

Appendix C

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774-922-4626 www.gassafetyusa.com

Report to

Damascus Citizens for Sustainability(DCS)
25 Main Street, Narrowsburg, New York 12764
mail to: P.O. Box 147, Milanville, PA 18443

Extended Report on a Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan, New York City, New York

11 March 2013

by

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[This report is subject to revision.]

EXECUTIVE SUMMARY

DCS requested that GSI extend the work effort described in our initial Report on a Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan, New York City, New York (16 December 2012) to assess the practicality of developing an estimate of methane emissions in Manhattan. Specifically the effort was to focus on providing an estimate of methane emissions that could be used in evaluating the role of natural gas leakage in Manhattan with respect to fossil fuel dependence, climate impacts and other environmental and economic concerns.

Currently the greenhouse gas equivalence of methane is widely accepted as at least 20 times the effect of carbon dioxide over a 100-year time frame. In

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other words, leakage of 1/20th, or 5%, of the methane moving through a natural gas production-transport-distribution system will effectively double the greenhouse gas impact of the use of that natural gas. That is, leakage of only 5% of natural gas from point of production to point of use would eliminate any greenhouse gas advantage of natural gas compared to other fossil fuels. More complex efforts by others have looked into the greenhouse gas emissions advantages of using natural gas instead of other fossil fuels. It appears that those more elaborate efforts are settling in at ≤3.2% gas loss to leakage as the maximum leakage rate at which use of natural gas retains an advantage. Hence, the loss of even a few percent of gas during production, transport, distribution and utilization is critically important to management and planning of present and future national and international energy supply and utilization systems. Therefore, it was concluded the extended GSI work effort should be focused on the need to assess total methane emissions. The available data was from Manhattan. Among the production, transport, local distribution and utilization systems, this work addressed the collective effect of only local gas distribution and utilization systems, along with any other methane sources that might be present in Manhattan .

GSI efforts for this extended report focused on three objectives: (1) find existing estimates from industry, government or other sources, of the amount of methane being released in Manhattan, (2) develop such an estimate from the ground-level methane data collected during our preliminary investigation of methane levels in Manhattan, and (3) compare those estimates and consider their implications with regard to broader environmental and economic concerns. Since this investigation was limited to Manhattan (augmented with comparative data from the Bronx, and other areas across New York and Connecticut), ConEd is the relevant gas distribution company.

An examination of existing estimates, or methods for estimating, methane emissions led to the conclusion that such estimates have little basis in actual data. Natural gas companies are required to file yearly reports of Lost- and-Unaccounted-for (LAUF) gas. Presumably these reports would approximate the amount of gas leaked from the pipelines and other infrastructure of the reporting companies. However, the meters in those gas systems are only required to be accurate to ±2%. Each such system may contain hundreds of thousands of meters. Each meter is subject to normal wear and tear. Another problematic issue is the reported LAUF gas volume may incorporate other gas volumes by rule, contract, regulation, or for other administrative reasons. Consequently, the annual reported LAUF gas volumes should not be regarded as reliable estimates of the amounts of gas actually lost or emitted to the atmosphere. However, since the LAUF gas volume is ultimately based mostly on measurements using meters that are accurate to ±2%, it follows that long-term average LAUF values should provide a reasonably meaningful mean with a ±2% variability. A ten-year average LAUF for ConEd was 2.2% with a range of 0.4 to 4.3%, i.e, ±2% variability. The 10-year-average-LAUF based estimate of annual methane emissions for the entire ConEd system was 2.2% or about 6.6 billion cubic feet per year.

The apparently most widely used method for estimating gas leakage and methane emissions from gas pipelines appears to be from a 1996 report by the U.S. Environmental Protection Agency and the Gas Research Institute (EPA/GRI). Estimates generated using the EPA/GRI 1996 method have such a wide confidence interval (±65%) that their general accuracy and usefulness is questionable. The report recognizes the likely importance of gas leaks that are undetectable by the standard industry leak detection practice, but the estimation method makes no attempt to account for such undetectable leaks. Finally, a related report of a more thorough study of cast iron pipelines in Brazil, suggested that the EPA/GRI method may provide estimates that are too low by almost half. Application of the EPA/GRI method to the pipeline statistics for the entire ConEd system generated an estimated methane emissions rate of 1 billion cubic feet per year, which can be meaningfully compared to the 10-year average ConEd LAUF gas estimate of 6.6 billion cubic feet per year. Since most leakage in gas delivery systems occurs from the pipes in the system, such a disparity between the EPA 1996-based estimate for ConEd pipeline leakage and the 10-year average ConEd LAUF gas volume would seem to indicate problems in one or both of those estimates.

During the research for this Report, we thoroughly reviewed the methane data collected by GSI during the previously reported Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan. We also reviewed the meteorological literature and meteorological data available for Manhattan. Based on that information we developed a simple model (patent pending) that could process our preliminary Manhattan methane data and meteorological data from local sources to generate a preliminary estimate of total methane emissions in Manhattan. The resulting estimate was the flow of methane to the atmosphere from all sources in Manhattan. Such an estimate can be used to assess the relative importance of those emissions in terms of methane as a greenhouse gas (GHG) and the relative impact of gas service/use in Manhattan in a broader climate/GHG context. Wherever reasonable in the application of the model, input values were selected conservatively, so that any errors in the result should be to the low side.

The resulting methane emissions estimate for Manhattan alone was 8.6 billion cubic feet per year, or about 2.86% of the 300 billion cubic feet of gas handled by the entire ConEd system each year, even though Manhattan comprises only about 5% of the land area and one-third of the customers in the ConEd service territory. There are also substantial losses that occur in the natural gas system before natural gas reaches the ConEd distribution system. It, therefore, appears inevitable that the loss of gas in the system serving NYC via ConEd is above the simple critical level of 5%, and well above the more elaborately derived critical levels of ≤3.2%. That is, the methane leakage in the system serving NYC through ConEd is likely already at a level where the methane leaked has as much or more climate impact as the remaining approximately 95% of the gas that is actually usefully burned by consumers in NYC. This necessarily raises doubts about the claimed value of natural gas as a "clean bridge fuel". Further work should be done to verify the findings we report here and to identify specific methane sources, as well as to improve natural gas leak prevention and management. Furthermore, the evidence suggests that leakage from natural gas systems has a more substantial role in climate change than was believed that has only recently begun to be appreciated.

Panoramic image looking south from the upper deck of the 'Top of the Rock' observation deck on Rockefeller Center. Image taken and assembled by Daniel Schwen on Dec 6th, 2004. {GFDL Wikipedia}

INTRODUCTION

In our initial report (dated 16 December 2012) on the preliminary investigation of ground-level ambient methane levels in Manhattan, New York City, New York we stated, “Further work is needed to determine whether an approximate estimate of the amount of methane being released to the atmosphere can be developed from the data generated by this preliminary methane survey.” To that end our efforts have focused on three objectives: (1) find existing estimates of the amount of methane being released in Manhattan from industry, government or other sources, (2) develop such an estimate from the ground-level methane data collected during our preliminary investigation, and (3) to compare those estimates and consider their implications with regard to broader environmental and economic concerns. Since this investigation was limited to Manhattan (augmented with comparative data from the Bronx, and other areas across New York and Connecticut), ConEd is the relevant gas distribution company.

Available Estimates of Methane Emissions in Manhattan

There are readily available documents that imply measurement-based estimates of methane (natural gas) releases in Manhattan have been developed.[3,4] However, review of those estimates leads to the conclusion that they are all largely based on other estimates, some periodically updated, but apparently never actual measurements of gas emissions in the field. This is presumably due in part to the historical lack of readily available, reliable approaches to actually measure methane concentrations and calculate methane emissions under field conditions.

LAUF Gas

Among the more prominent of such estimates-based-on-other-estimates would seem to be the Lost And Unaccounted For (LAUF) gas that companies are required to report to the New York State Department of Public Service (NYSDPS). Actually, the reported LAUF is a calculated number that includes volumes actually measured by meters in the gas distribution system along with various add-ins and deductions that are matters of contract, regulation, or used for operational accounting reasons. In addition to the arbitrariness of the add-ins and deductions, gas meters are only required to be accurate to ±2%. Malfunctions leading to metering errors of more than 2% can be expected to occur. It is important to realize that the estimation and reporting of LAUF gas was never intended to represent actual losses of gas from the gas distribution system, but to facilitate annual reconciliation of costs for gas purchased to revenues for gas sold while providing incentive to minimize actual loss of gas.[5] The reliability of LAUF numbers as estimates of actual gas losses is easily appreciated in the following statement (with original footnotes) found in a New

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[3] ConEdison Gas Long Range Plan 2010-2030, December 2010 [accessed at http://www.coned.com/PublicIssues/PDF/GLRP1210c.pdf], and various ConEd annual and other reports.

[4] Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 - 2009, USEPA, April, 2011., Annex 3 (PDF) (232 pp, 9.6 MB) - Methodological Descriptions for Additional Source or Sink Categories. [http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html].

[5] NYS DEPARTMENT OF PUBLIC SERVICE, STAFF WHITE PAPER ON LOST AND UNACCOUNTED FOR (LAUF) GAS, issued January 27, 2012. [White paper accessed at http://www.google.com/search?client=safari&rls=en&q=NYS+DEPARTMENT+OF+PUBLIC+SERVICE,+STAFF+WHITE+PAPER+ON+LOST+AND+UNACCOUNTED+FOR+(LAUF)+GAS,+Hearing+Exhibit+No.+76,+GRP-15&ie=UTF-8&oe=UTF-8]

York State Department of Public Service Staff White Paper on Lost and Unaccounted for (LAUF) Gas[3] (NYSEG is New York State Electric and Gas Corporation):

> "<u>Negative Losses</u>
> Staff must address negative losses because NYSEG[12] has experienced consistent negative losses for the past 3 years. Negative losses are physically impossible. However, consistent year to year calculated negative losses are possible when the offset[13] between the set of meters reading gas in and the set of meters reading gas out is negative and the natural variability is less than that offset. Additionally, natural variability in the LAUF can produce negative losses in some years for LDCs whose offset is positive.
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> [12] Case 09-G-0669
> [13] Two sets of meters will never provide the same measurement. The difference between those two measurements is defined as offset."
> Note: LDCs are Local Distribution Companies

NYSEG LAUF gas values over those "past three years" (2008-2010) averaged -0.359%, while the ConEd average LAUF for the same three years was +1.249%. NYSEG is not ConEd, but gas metering and related LAUF errors inevitably affect the reported LAUF gas amounts of every company and probably in different and unforeseeable ways that change from year to year. Unaccounted for gas estimates are also reported annually to PHMSA[6]. When ten years (2002-2011) of those reported values were examined for this report, they were not the same as those stated in the NYS DPS Staff White Paper[3], presumably due to different reporting requirements. Though consistently low, the NYSEG unaccounted for gas reported to PHMSA, were never negative, ranging from 0.1% to 0.3% for the eight years 2004-2011. Though not implausible, such consistent and low numbers are interesting given that meters used in gas systems are only required to be accurate to ±2%. For the ten years 2002-2011, ConEd reported annual unaccounted for gas percentages ranging from 0.4-4.3. In contrast to the consistently low numbers of NYSEG, the ConEd numbers appear to have a variation of very close to ±2% around a mean of 2.2%. Coincidentally, 2.2% also happens to be the mean of all unaccounted for gas percentages reported to PHMSA from 2002-2011, though among those numbers individual annual reports ranged from -28% to +109%. Such examples serve to illustrate that LAUF numbers provide little if any useful insight into the actual amounts of gas lost from companies' gas distribution systems at any given time, or over a given year. Still, it is helpful to consider a bit further the implications of the average

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[6] PHMSA - US Department of Transportation Pipeline and Hazardous Materials Safety Administration. Lost and Unaccounted for Gas reports accessed at http://www.phmsa.dot.gov/portal/site/PHMSA/menuitem.ebdc7a8a7e39f2e55cf2031050248a0c/?vgnextoid=a872dfa122a1d110VgnVCM1000009ed07898RCRD&vgnextchannel=3430fb649a2dc110VgnVCM1000009ed07898RCRD&vgnextfmt=print

unaccounted for gas percentage of 2.2%.

A Little Bit Matters

A loss of 2.2% might seem almost trivial. Each gas consumer, based on the required accuracy of the meter that measures gas consumption, can expect that they may be over or undercharged by as much as 2% anyway. Why, then, should anyone concern themselves with a loss of a few percent over the distribution system as a whole? A first answer would be a fair allocation of the monetary cost of the lost gas. In 2011 ConEd had total gas sales and transportation revenues of around 1.5 billion dollars, 2.2% of which amounts to 33 million dollars. That is a substantial amount of money and has to be accounted for and fairly allocated, a process that is regulated by the NYS Department of Public Services. Again, though, in the grand scheme of things, the consequences for each customer are relatively minor, only 0.2% more than the ±2% of metering accuracy. So, we are still left with the question, why does such a seemingly small amount matter?

There are two closely related reasons. One, it remains that, regardless of the reporting of the amounts of lost and unaccounted for gas, those reported amounts do not seem to provide a reliable indication of the actual losses of gas that are occurring. Two, when methane, which makes up over 90% of natural gas, escapes from the distribution system it can accumulate to pose direct risks of injury and property damage. A less obvious but greater global concern is the role of methane as a potent greenhouse gas. Any leakage of methane poses an effectively invisible, but potentially substantial threat to human health and the environment. These reasons provide a means of understanding why the actual amounts, and locations, of even seemingly small gas losses matter.

Even small natural gas leaks in confined spaces are dangerous, posing explosion and asphyxiation hazards. When a small underground gas leak finds a pathway to an enclosed space, such as a manhole, the gas can accumulate to explosive levels (5%-15% methane). Basements and other poorly ventilated spaces can also accumulate leaked gas to hazardous levels. Explosions related to such accumulations of leaked gas, though not common, are recurrent wherever natural gas is used. In addition, where even relatively small amounts of gas are leaked into the soil for extended periods, vegetation will be damaged, loss of urban trees being a common impact. Still, the ConEd record of gas safety with regard to direct hazards is relatively good.

ConEd, like other gas companies, has a routine program to detect, manage and repair leaks. However, the objective of such leak control programs is to detect leaks, not measure the amount of gas lost through them. Such measurements would be impractical, especially for the potentially very large numbers of very small leaks that can be expected to develop in pipe systems that contain substantial amounts of old pipe. Over 70% of the cast iron pipe in the ConEd system is over 100 years old, and almost all was installed before 1930, i.e., is more than 80 years old.[3]

EPA Leakage Estimates for Natural Gas Pipelines

In this scenario, we are left with potentially large numbers of small leaks, and smaller numbers of larger leaks in gas pipe systems. Measurement of the gas losses that occur through such leaks is in practical terms impossible. Most of the small leaks will never be identified, let alone measured. How, then, does anyone arrive at some reasonable estimate of how much gas is being lost? In 1996 the U.S. Environmental Protection Agency (EPA) released an approach for estimating such losses.[7] This approach is of considerable importance because it has become the basis for international estimates of methane/natural gas leakage as well.[8]

The EPA approach[7] is relatively simple, based on 4 types of pipe materials, cast iron, unprotected steel, protected steel, and plastic. The estimated leak rates for the 4 types of pipe were based on data collected in a 1992 study by the EPA and the Gas Research Institute (GRI). The length of pipe of a given type in a system is multiplied by an estimated leak rate for a given length of that type pipe. For cast iron pipes, the oldest and leakiest type, the estimated leak rate is in standard cubic feet per mile of pipe per year (scf/mile-yr). That study looked at a total of 21 samples of cast iron pipe. The estimated methane leak rate for cast iron pipe was 399,867 scf/mile-yr (with a 90% confidence interval of 227,256). This was reduced by another factor intended to account for the amount of methane that would be biologically oxidized in soil before escaping into the atmosphere to produce a “Methane Emission Factor” for each type of pipe. After that reduction the estimated emission factor for cast iron pipe became 238,736 scf/mile-year (with a 90% confidence interval of 152,059).

The 90% confidence intervals and numbers of samples are mentioned in this discussion because it is important to understand how imprecise these estimates

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[7] EPA/GRI. Methane Emissions from the Natural Gas Industry. Volume 9: Underground Pipelines. June 1996. http://www.epa.gov/gasstar/documents/emissions_report/9_underground.pdf.

[8] IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>.

are. The numbers seem so imprecise that their usefulness seems questionable. The statistically strongest data set in EPA/GRI[7] was that for cast iron pipe. The data indicates that there is only 90% confidence that the true mean leak rate for cast iron pipe is somewhere in the range of 399,867±65%, that is, somewhere between 172,000 and 626,000 scf per mile of pipe per year.[9] The 90% confidence level seems low for an estimate that has implications as broad and important as this one. Accuracy is critical in estimating emissions of the second most important greenhouse gas, methane, when these estimates are being used in both national and international estimates for climate change modeling and planning of mitigation and response measures..[8] At least a 95% confidence interval would seem more traditional and appropriate to the purpose. However, back calculation from the 90% confidence levels and sample numbers in EPA/GRI[7] report indicate that the 95% confidence intervals would extend below zero for unprotected steel and plastic pipes, and would approach zero for protected steel. In fact, in the case of plastic pipe, with a high variability (range 0.008 to 61 std.cu.ft. per leak per hour) and the lowest number of samples (N=6), even at the liberal 90% confidence level, the lower limit of the confidence interval was -60,000 std.cu.ft. per leak per year, implying the impossible situation that relatively large amounts of gas could be taken in instead of emitted by leaks in plastic gas lines. One might reasonably set aside the issue of implied negative leak rates, and allow that leak rates below zero cannot occur. Even from this perspective, one is left with the predicament that the EPA/GRI[7] data for plastic pipe do not distinguish at a 90% confidence level between 260,000 scf per leak per year and no leak at all.

A Leakage Estimate from Comgas in Brazil

The EPA estimate approach is still the international norm, but more recent work reported out of Brazil provides a different picture.[10] That study by the Brazilian natural gas distribution company Comgas used a different approach to selecting samples, and a very conservative approach to disregard all suspiciously or inexplicably high leak rates. The Comgas study was apparently continuous from 2005 through at least 2009 as part of a pipe system upgrade program. Consequently, pipe sections selected for testing were each almost

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[9] EPA/GRI[7] is not clear regarding whether a one-sided or two-sided confidence interval was used. The statement, "an overall accuracy of ±65% based on a 90% level of confidence" suggests a two-sided confidence interval was used, but repeatedly in footnotes to tables "upper bound minus the mean" may indicate a one-sided confidence interval was used. We assumed that all confidence intervals referred to in EPA/GRI[7] were two-sided.

[10] Carey Bylin et al. 2009. New measurement data has implications for quantifying natural gas losses from cast iron distribution mains. Pipeline and Gas Journal. (www.pgjonline.com).

certainly considerably larger than the minimum 20-foot sections in the EPA/GRI 1992 study[11] and were effectively more randomly selected. Random selection based on work scheduling without regard to prior detection of leaks combined with measurements of longer pipeline segments means the Comgas study would more likely measure total leakage, where the EPA/GRI approach was based on detection of leakage before testing. In the course of the Comgas work in Brazil, 912 pipe sections were tested, compared to only 21 in the EPA/GRI 1992 study. The Brazilian cast iron pipe system was reported to be otherwise comparable to the U.S. cast iron system studied by EPA/GRI in 1992. The Brazilian cast iron pipe, however, would likely be considerably younger than that in the ConEd system in which 70% of the cast iron pipe is over 100 years old. Instead of a methane leak rate of 399,867 scf/mile-yr the Brazilian study found a leak rate of 750,513 scf/mile-yr. It is interesting that though the Brazilian study may be regarded as contrasting with the EPA/GRI, in fact, it actually is statistically compatible. We back calculated the standard deviation of the EPA/GRI[7] cast iron pipe results and concluded the 750,000 scf/mile-yr appears to be within 99% confidence bound of the EPA/GRI[7] study. That is, the findings of the two studies do not seem to conflict. The Brazilian is simply a more robust, larger study that should provide a more accurate estimate and is statistically compatible with the EPA/GRI estimate.

Yet, even the higher Brazilian numbers may be too low because data from pipe sections with suspiciously or inexplicably high leak rates (>1,991,444 scf per mile per year) were excluded. The excluded data was 15.4% of the total data. The concern behind that elimination of high leak data was that such data could be caused by measurement procedural problems in the field or unmapped service lines connected to the cast iron mains. It would seem likely that leaks of this size would result in noticeable mercaptan odors and consequent leak reports. Nevertheless, it also seems reasonable that such large leaks may develop slowly and exist for some time before odor motivates reports of suspected leaks, though 15.4% of pipeline test sections seems implausibly high. The concern that such high data are due to procedural difficulties or unmapped services seems reasonable, but one avoided at the risk of entirely missing some actual large leaks. For example, if the tested sections are relatively long, there could be several moderate sized leaks that collectively cause leak rates above

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[11] The actual lengths of cast iron pipe sections were apparently variable and not clearly specified in the 1996 EPA/GRI[7] report of the results of the 1992 EPA/GRI study of pipe leak rates: (on page 20 of that report) "The segment to be tested was either: 1) a service which was isolated … at the service-to-main connection and the customer's meter, 2) a short segment of main (at least 20 feet long) containing the detectable leak which was isolated by capping both ends, or 3) a long segment of main containing multiple leaks…isolated by capping off each end. … For cast iron pipes, a segment test approach was used since many undetected leaks are known to exist in cast iron."

the Comgas sample rejection level. Without knowing the lengths of the Comgas test sections, it is not possible to resolve this doubt. For present purposes, it is sufficient to let the Comgas test results stand as reported.

Estimates of Methane Leakage for ConEd based on EPA/GRI and Comgas Reports

Most of the oldest and leakiest pipe in many natural gas systems is cast iron. About 30% of the mains in the ConEd pipe system are cast iron, with another 30% unprotected steel, the next leakiest type. Now, using the EPA Methane Emission Factor extrapolation approach would seem reasonable enough, in fact, a practical necessity given the amount of underground pipe in natural gas distribution systems. For example, ConEd has about 1300 miles of cast iron mains, with similar amounts of unprotected steel, all of which feed eventually into hundreds of thousands of smaller service lines. Clearly the amount of gas leaking from each segment of such an extensive gas pipe system cannot be monitored continuously.[12] Given the soil conditions under the streets of Manhattan, biological oxidation of methane is probably limited. So, if one applies the (no soil methane oxidation) EPA Methane Leakage Factor of (rounded) 400,000 scf/mile-yr for cast iron mains to the 1300 miles of cast iron pipe in the ConEd system one arrives at estimated methane emissions of 520,000,000 scf/yr. If one uses the Brazilian Comgas cast iron pipe leak rate this becomes 975,000,000 scf/yr, which could also be too low.

Other Leak Sources and Other Estimates

One could similarly generate estimates for the other likely sources of gas leakage in the ConEd system in accordance with EPA estimating methods. In fact, beginning in 2010 ConEd, along with most other large emitters of greenhouse gases, has to file a report of estimated emissions of GHGs, including methane, with the EPA every year. However, during the preparation of this report only the 2010 GHG emissions report for ConEd had been filed and released by EPA. That 2010 ConEd report contained only volumes of natural

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[12] In fact, in general any given section of pipe is checked every 1-3 years. Type 3 leaks that are detected but do not present an explosion hazard at the time of detection, and are deemed not likely to subsequently present such a hazard, are not repaired but put on a somewhat more frequent inspection schedule to assure they do not increase to a hazardous level. That is, they are left to continue leaking until they increase to an explosion hazard level or are repaired under routine leak repair efforts. Such unrepaired Type 3 leaks effectively release methane emissions without a control effort because they do not present an immediate or foreseeable explosion hazard.

gas delivered, which totaled 286,962,094,000 scf. The number of potential sources of leaked methane, besides cast iron pipe, in the ConEd system is large, perhaps explaining why the 2010 ConEd GHG emissions report to EPA is empty. For the purposes of this report, a simpler approach may serve the immediate purpose of showing that presently reported numbers are not reliable and approaches to actual measurement are needed.

Consider in this regard that through the EPA Natural Gas STAR program ConEd has been credited with reducing methane emissions by 4,393,613,000 scf cumulatively since 1993. That 18-year (or so) cumulative reduction barely makes up for somewhere between 4 and 8 years of the estimated ongoing leakage from cast iron pipes alone, depending on the leak rate factor used. ConEd reported to the EPA GasSTAR program that in its best single year, 2008, it reduced methane emissions by 158,795,000 scf. That is, in its best year, ConEd eliminated the equivalent of barely 30% of just one year of losses from the cast iron pipe alone. So, given there are still 1300 miles of cast iron pipe in the ConEd system, and there are many other potential leaks in the ConEd system, ConEd may well be losing ground with respect to overall net methane emissions. Further, if one considers that the total gas handled annually by ConEd amounts to about 300,000,000,000 scf[1], then the estimated cast iron pipe leakage alone amounts to in the range of 0.17-0.33%, and this estimate could still be low.

When Is a Leak a Leak?

When It Is Detectable.

Another matter worth considering is the functional definition of a leak. In the ConEd Long Range Gas Plan (2010)[1] there is the following statement (including associated original footnotes).

> "Con Edison also performs extensive leak repairs annually and has managed to reduce the backlog of leaks … . In 1988, the gas leak backlog was just over 15,000 leaks and year-end 2009 leaks were under 1,400. Most of the leaks in the leak backlog are Type 3[23] leaks which are not hazardous. We enter each winter with less than 100 hazardous leaks. Gas leak repairs are a major commitment of our O&M expenses. Con Edison has the highest amount of leak reports issued annually of all NYS utilities. Con Edison has committed to the NYS Public Service Commission that ConEd will maintain a leak backlog of less than 1,600[24] leaks at the end of the year.
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> [23] A Type 3 leak is not immediately hazardous at the time of detection and can be reasonably expected to remain that way. However, Type 3 leaks shall be reevaluated during the next required leakage survey or annually whichever is less.
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> [24] NYS PSC mandates a leak backlog less than 1600 leaks at the end of the year."

The contention of ConEd regarding the total number of leaks may be reasonable given industry leak detection practices, but not at all accurate in terms of actual total pipe leakage. A similar statement has to be made with respect to the previously discussed 1996 EPA/GRI report[7] providing the now widely used methane emission factors for gas pipelines.

Cast iron gas distribution (pipe) mains have been in the ground longest among all the predominant pipe types in the commercial natural gas system. EPA/GRI[7] reported that cast iron pipelines were found to be much leakier than the pipelines of the other pipe materials. The high leakage from cast iron pipes is due to large number of small leaks, "For cast iron pipes, a segment test approach was used since many undetected leaks are known to exist in cast iron." EPA/GRI[7] also reported experiments indicated 40.3% of the methane leaked from cast iron pipes was oxidized during its rise to the soil surface, but only 1.8-3.0% for the other pipe types. Soil methane oxidation rates measured around cast iron pipes were much higher than for other types because the methane leakage is spread more widely around and along cast iron pipes. For the other pipe types, detected leaks tended to be larger but fewer in number resulting in more concentrated methane and less oxidation in the soil.

So, when, then, is a leak a leak? When gas escapes from a pipeline is it like the proverbial tree falling in the forest? When gas escapes from a pipeline is it a leak, or is it not a leak until the gas company detects it? The following quote from the EPA/GRI report[7] explains the typical industry approach to detecting gas leaks.

> "Gas distribution operators use leak detection procedures to locate and classify leaks for repair. To identify a leak in a section of pipe, a portable hydrocarbon analyzer or flame ionization detector (FID) was used to screen immediately above the ground level while walking the pipeline. Any excursions above the background level (typically 2-3 ppm) may indicate a nearby leak."

However, the EPA/GRI[7] report also states that "many undetected leaks are known to exist" in cast iron gas mains. That is, there are undetectable leaks, and potentially a lot of them. Again quoting the EPA/GRI[7] report (page 20),

> "This technique was based on testing leaks which are detected using leak survey procedures (i.e., detected leaks), and may exclude smaller or more diffuse leaks that are not detected at the soil surface."

Now, having established there are undetectable leaks, and since undetectable leaks are undetectable, they are not included in the leak counts of ConEd, or any other gas company using a similar leak detection method. Similarly, since this method was used in the EPA/GRI[7] pipeline leakage study to select pipe sections for leak testing, whether or not it accounts for any undetected leaks is unclear. That report states,

> "The leak flow rate measurement used should have accounted for all leaks in a pipe segment. ... The segment of pipe tested was also surveyed to determine the number of detected leaks and the corresponding concentration of methane detected for each leak in the segment."

However, it is not clear whether or how this survey "to determine the number of detected leaks" might have included "undetectable leaks".

So, we are left with data in industry records and the widely used EPA/GRI[7] study results that by default do not seem to address "undetectable" leaks even though those records and that report clearly indicate substantial amounts of such leaks do occur. At least we do know that a leak is a leak no matter how small.

A Consideration of Undetectable Leaks

In Cast Iron Pipe

At this point one may wonder what then might an undetectable leak be like and what difference, if any, might such leaks make? The question would seem to resolve to how many undetectable leaks might there be that would escape detection by the typical industry leak detection method. Leaks are usually detected by surveying at the ground surface above a pipe with an FID instrument set to alarm if methane (actually combustible gas) levels rise above background levels. EPA/GRI[7] accepted and included in their emission factors an estimate by Southern Cross Corporation that 15% of detectable leaks are simply missed using the standard leak survey. It would seem to make sense that those 15% might be predominantly smaller, hence, harder to detect leaks.

Actual individual leak data were not provided in the EPA/GRI[7] report except for the 6 data points for plastic pipe. The lowest leak measured, hence, presumably detected, was 0.008 scf per leak per hour. It is not clear, however, that this was a leak that actually allowed detection as the next nearest leak rate, 0.700 scf per leak hour, was approaching 100 times larger. EPA/GRI[7] reported that this 0.008 scf per hour leak value was a potential statistical outlier. Coincidentally, it also happens to be the smallest of 6 data points, and, therefore, comprises roughly the bottom 15% of the leaks, i.e., the percentage estimated to be routinely missed in leak surveys. So, if the 0.008 scf/leak-hour value is disregarded, among the remaining five data points, the next highest 3 fall in the range of 0.7-1.62 (average 1.15) scf/leak-hour. Since these are the only data immediately available, we will assume for this discussion that the smallest leak that can be reliably detected using the industry leak detection method will have a leak rate of 1 scf/leak-hour.[13] As discussed below, it matters little whether the actual undetectable leak is 1 scf per hour or considerably lower.

It would seem to follow that if two 1-scf-per-hour leaks were next to each other, then at the soil surface they would present the same methane concentration as one 2-scf-per-hour leak. That is, they would be detectable. So, then, at what distance of separation would they cease to be detectable? Gas Safety, Inc. experience with gas leak detection indicates that under a paved surface small leaks are detectable over a surrounding, roughly circular area in the range of 20-25 feet in diameter, and about half that if the soil surface is not paved over. Recall the test sections in the EPA/GRI[7] study were around 20 feet which would, therefore, imply that small (≤1 scf -per-hour) leaks separated by more than 20 feet would not likely have been detected or measured in that study. To provide some notion of what such leaks might mean, one could assume there ought to be a range of such small undetectable leaks that should vary from just more than zero to just less than 1 scf per hour, which would generate an average undetectable leak size of 0.5 scf per hour.

Because undetectable leaks are undetectable, there is at present no data that provide direct indications how many there might be per length of pipe, regardless of the material the pipe is made of.[14] Nevertheless, a rough indication can be extracted from the data in the EPA/GRI[7] report. For ten reporting gas distribution companies, there was an average of 1.38 leak repairs per mile of cast iron pipe. It follows that if a repair were undertaken, then it was because a detectable leak had been found. This is actually a conservative approach because a repair implies a detected leak, but not all detected leaks are repaired (within a year of detection). EPA/GRI[7] estimated the average

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[13] Based on decades of experience in gas pipeline leak detection, Gas Safety, Inc, considers such small leaks unlikely to be detectable by conventional gas leak surveys in open field, unpaved soil surface conditions. In urban settings, i.e., where gas lines are under paved surfaces that can cause methane to accumulate in the soil or in underground channels or spaces, a larger proportion of such leaks might be detected. The urban/rural setting of the EPA/GRI[7] sampling sites was not specified.

[14] Except for the Comgas study[7] in Brazil regarding leaks from cast iron pipes, implications of which are discussed later in this report.

number of active detectable leaks per repair was 2.14. Converting 1.38 repairs per mile to the distance between detected leaks (repairs) yields one detected leak for every 0.725 miles of pipe. Applying the EPA/GRI[7] estimate of 2.14 actual detectable leaks per repair reduces the distance between detectable leaks to 0.725/2.14=0.339 miles. Since the (presumably) total leak rate for cast iron pipe was 399,867 scf per mile per year, the total leak rate for the average length of pipe between two adjacent detectable leaks, i.e., 0.339 mile, would be (0.339 X 399,867) = 135,469 scf per year.

We are trying to develop some understanding of the potential importance of undetectable leaks. The EPA/GRI[7] cast iron leakage rate supposedly includes both detectable and undetectable leaks. So, if we deduct the rate for detectable leaks in cast iron pipe from the total leakage, we should have the rate for undetectable leaks. Unfortunately, there was no reported leak rate per leak in cast iron pipe because, as previously discussed, cast iron pipe typically has a large number of small leaks. As an alternative, we used the leak rate of 52,748 scf per leak per year for the most similar pipe, unprotected steel. Each detectable leak is on average 0.339 miles from the next, and each 0.339 miles of pipe has a total leakage of 135,469 scf per year. The undetectable leakage should be the difference between the total leakage (135,469 scf/yr) and leakage from the detectable leak (52,748 scf/yr), which is 82,721 scf per year. This then is an estimated average leakage from undetectable leaks for the pipe between each two detectable leaks, which occur on average every 0.339 miles. Converting this undetectable leakage rate to leakage per mile per year yields 244,000 scf per mile per year.

This volume of leakage would be accounted for by one undetectable 0.5-scf-per-hour leak every 95 feet along the cast iron pipeline. Perhaps, though, the actual undetectable leak size is smaller. Even if the average undetectable leak were smaller, say, 0.2 scf per hour, then the interval between undetectable leaks that would account for 82,271 scf/0.339 mile per year would be 39 feet, still farther apart than the likely 20-foot interval that might make 1-scf-per-hour leaks detectable and well beyond the ends of the 20-foot test segments used in the EPA/GRI[7] study. So, it matters little whether the threshold for leak detection is 1, 0.5 or 0.2 scf/hour, the implications of undetectable leaks remain large, at least for cast iron pipe. With regard to the plausibility of this estimate of leakage from undetectable leaks in cast iron pipe, one may consider that adding this 244,000 scf per mile per year to the EPA/GRI[7] estimated 400,000 scf per mile per year (presumably based on pipe sections with detectable leaks) generates a total estimated leakage of 644,000 scf per mile per year, still well below the 750,000 scf per mile per year total leakage actually measured in the Comgas study in Brazil.

Undetectable Leaks In Pipelines Made of Other Materials

This potential importance of undetectable leaks cannot be simply ruled inapplicable to pipes made of other materials. There seems no reason to rule out occasional minor manufacturing defects, damage during installation and due to natural underground processes and animal and human activities after installation. Indeed, unprotected steel is subject to corrosion problems, as is protected steel, though to a lesser degree. The question becomes, then, how to generate an estimate of the potential importance of undetectable leaks in steel and plastic gas lines. One approach would seem to be to again exploit the logical association of repairs to detected leaks. It was estimated above that leaks as large as 1 scf/hour and as close together as every 20-25 feet would likely be undetectable using the typical industry leak detection method. Once again referring to EPA/GRI[7], the reported repair interval for unprotected steel pipeline was 1.09 repairs per mile per year, and 0.08 for both protected steel and plastic. These can be converted, as above, to miles between adjacent repairs, which are 0.917 miles for unprotected steel and 12.5 miles for both protected steel and plastic. Now, it would seem reasonable to conclude if pipe injury/defects/etc. were causing detectable leaks in cast iron, then undetectable leaks in other pipe materials will ultimately be due to the same causes. So, if leaks have the same causes in all pipe materials, then the ratio of detectable leaks to undetectable leaks should be reasonably similar for all pipe materials.

Applying this same-ultimate-causes-for-leaks reasoning and extrapolating the estimated undetectable leakage rate for cast iron pipelines to unprotected steel pipelines yields an effective distance between detectable leaks of 0.429 miles, and an estimated leakage from undetectable leaks of 47,543 scf per year for each 0.429 miles of pipe, or 111,000 scf per year per mile of unprotected steel pipeline. Extrapolating the above approach indicates flows from undetectable leaks are likely to be <10% of those for detectable leaks in plastic and protected steel pipes. It should be borne in mind, however, that these pipe materials have not yet progressed far into their expected service lives, whereas cast iron pipes still in service are old, 70% over 100 years for ConEd. It would seem that monitoring for leaks previously regarded as undetectable would be advisable to assure environmentally safe management of natural gas leaks in a future where so much more gas and presumably so many more gas lines are expected to be in use, regardless of the pipe material.

Why Are More Accurate Measures of Natural Gas Leakage Needed?

Whether one considers the ConEd LAUF as reported to NYSDPS, or to PHMSA or to EPA based on factors given in EPA/GRI[7], the reality is we have little reason to believe any of these estimates provide a reliable indication of how much natural gas is leaking from natural gas distribution systems, or of how much methane that leakage is releasing to the atmosphere. Hopefully it is at this point obvious to the reader that actual identification and measurement of every gas leak, or even leakage of gas from every segment of gas pipeline in service, is an impossible, and perhaps meaningless task. In the end there remain three objectives:

1. Fair and reasonable allocation of unaccounted for costs in the natural gas public service system.
2. Prevention of hazardous situations related to accumulation of leaked gas to levels that are explosive or asphyxiating (to humans, animals or plants).
3. Mitigation of the expected climate affecting impacts of methane emissions to the atmosphere.

At present there are, as already discussed, procedures in place that achieve the first two of these objectives to a reasonably satisfactory level. The third, however, is not effectively addressed at all by those approaches, and apparently inadequately by currently used estimation methods based on EPA/GRI[7].

RESULTS

An Estimate Based on Ground-Level Ambient Methane Levels

We developed a method (patent pending) to generate a preliminary estimate of total methane emissions in Manhattan from the data collected by GSI during the previously reported Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan. The method appears to be broadly applicable to other trace gases, sites and situations. In the present case of Manhattan, such emissions estimates can be used to assess the relative importance of those emissions in terms of methane as a greenhouse gas (GHG) and the relative impact of gas service/use in Manhattan in a broader climate/GHG context. More precisely, the estimate that can be generated from the GSI Manhattan preliminary ground-level methane data is the rate of flow of methane from Manhattan to the atmosphere beyond.

The approach used is relatively simple. Only four pieces of information are needed to calculate a flow rate, in this case for methane from Manhattan into the atmosphere. What are the boundaries of the source area for the flow; in this case what are the effective boundaries for air flow to/from Manhattan? What is the concentration of methane in the air when the air enters the source area, i.e., Manhattan? What is the methane concentration when the air exits Manhattan? How fast is the air entering/exiting Manhattan?

The GSI preliminary Manhattan methane data provide a large set of (over 700,000) measurements of the concentration of methane at various points around the island, and other areas in the vicinity and region, at various times over a period of five days. The challenge is to sort that data into subsets such that the methane concentration data can be associated with air moving into Manhattan, picking up methane in Manhattan, and then departing, and how to estimate how much air was moving during the relevant sampling times. Fortuitously, during certain parts of the GSI Manhattan preliminary methane survey winds and survey pathways occurred in such patterns that evaluation of the methane concentration in air entering and leaving Manhattan is practical. In order to enable use of that methane data, it was necessary to gather information and data from meteorological literature and monitoring and reporting programs. The times and conditions of one relevant data subset from the GSI Manhattan methane survey were as follows.

The 29 November 2012 Methane Survey Data

From roughly 4 PM to 5 PM on the afternoon of 29 November 2012 a survey run was made along the west, south, and eastern sides of Lower Manhattan near the shorelines. At that time the wind was consistent, from roughly the southwest (compass bearing 240 degrees) at 8 miles per hour. These wind conditions and that survey path provided data for distinct upwind and downwind areas along the near-shoreline areas around Lower Manhattan. The upwind data provided methane concentration of air arriving on the island, while downwind data provided methane concentration of air departing the island on the same wind direction path. The City College of New York has a robust weather monitoring program. By accessing the NYCMetNet website an estimated height for the mixing layer of the atmosphere over Manhattan for the same time period was obtained.[15] The length of the travel paths in the upwind

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[15] The mixing layer is the lowermost layer of air in the atmosphere where air flows over and is influenced by the land or water surface below (see image on page 22). Above the mixing layer, winds tend to have a smoother, laminar flow, but within the mixing layer winds tend to have turbulent flows that cause most gases or aerosols released near the land or water surface to disperse rapidly laterally and vertically throughout the air to the upward limit of turbulent flow. The height of the mixing layer changes over time, but is consistent for time periods longer than necessary for the purposes of the current data interpretation effort. Height of the mixing layer and other meteorological data are accessible through the NYCMetNet, provided by the Optical Remote Sensing Laboratory of The City College of New York (ORSL), http://nycmetnet.ccny.cuny.edu.

and downwind portions of that survey run were estimated using Google Earth. These data were as follows:

Methane Concentrations in Ground-Level Air
Upwind 1.92 ppm ±0.003ppm (99.9999% Confidence Interval)
Downwind 2.165 ppm ±0.021ppm (99.9999% Confidence Interval)

Wind speed (speed of air entering/exiting Manhattan) 8 mph (11.7 feet per second)
Wind direction (from) WSW (compass bearing 240 degrees)
Manhattan wind cross-sectional length: 7 miles (36960 feet)
Mixing layer height: 2600 ft.[14]

These data can be applied in the following sequence of calculations:

To get the volume of air entering/leaving Manhattan per second:
Wind speed X wind cross-sectional length of Manhattan X mixing layer height =
11.7 ft/sec X 36960 ft X 2600 feet = 1.1 billion cubic feet per second

To get the amount of methane added while the air passed over Manhattan, take the difference between the upwind and downwind methane concentrations and apply it to the amount of air leaving Manhattan per second:
(Downwind methane concentration – Upwind concentration) X Volume of air leaving Manhattan per second =
(2.16 ppm – 1.92 ppm) X 1,100,000,000 cu.ft./sec. = 270 cubic feet per second

To get cubic feet per second of methane added by Manhattan to cubic feet of methane added per year:
Cubic feet per second added by Manhattan X 60 seconds per minute X 60 minutes per hour X 24 hours per day X 365 days per year =
270 cu.ft./sec X 60 sec/min X 60 min/hr X 24 hr/day X 365 days/ yr = 8,600,000,000 or 8.6 billion cubic feet per year.

This estimated annual methane flow rate from Manhattan is approximate. Each of the measured data values used could be a source of error. The methane data for a given time frame is highly reliable, 99.9999% confidence intervals ± <1% (0.021 ppm). However, methane concentrations in the air vary with location, time, wind, temperature, barometric pressure, humidity/precipitation, and the complex collective interactions of all these and possibly other factors. To examine the likely accuracy of the 29 November methane data used in the above Manhattan flux estimate other data subsets from the full data set were examined. Each of these data subsets was collected at different times, covered different locations on and off Manhattan island, and occurred under different weather conditions. Nevertheless each data set is still relatively large, the smallest containing over 2000 methane data points. The following subsets were identified and examined:

Manhattan mean methane levels relative to reference area for given date					
Date (2012)	11-27	11-29	11-30	12-09	
Wind (from)	NE	WSW	NE	NNE	
Mean Methane Concentration (ppm)					
					Means over all 4 dates
Manhattan	2.079	2.165	2.345	2.261	2.213
Reference Area	1.866	1.92	2.008	2.002	1.949
Increase while over Manhattan Island	0.213	0.245	0.337	0.259	0.264
99.9999% Confidence interval for all Manhattan and Reference Area Mean Methane Concentrations was ≤ 1 % relative (0.002 to .022 ppm)					

On 27 November data were collected on Manhattan island that generated a mean methane level of 2.079 ppm, while the average methane level traveling to NYC was 1.866 ppm. The wind that day was out of the NE (compass bearing 50 degrees) at an average speed of 5.8 mph. On this day the wind was blowing from the area travelled to arrive in Manhattan. Hence, deducting the average methane level before arrival in Manhattan, 1.866 ppm, from that measured in Manhattan, 2.079 ppm, indicates the increase due to methane sources on Manhattan island, 0.213 ppm. This compares reasonably well with the 0.245 ppm increase due to methane sources on Manhattan island on 29 November.

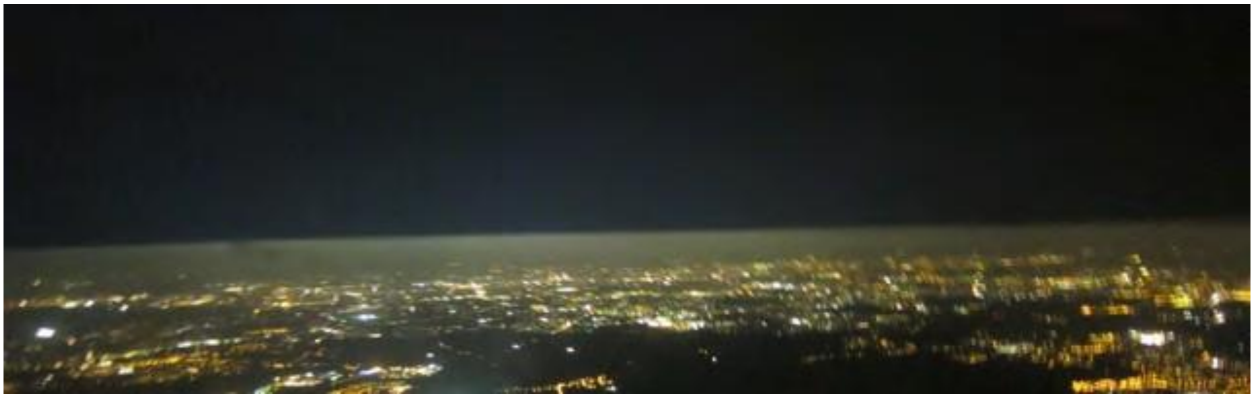
Similar data subsets were available in the 30 November and 09 December data sets, each day with different wind conditions and, consequently, different upwind areas used as sources of reference methane levels. On 30 November the indicated methane concentration increase due to methane sources on Manhattan island was 0.337 ppm. On 09 December the increase was 0.259 ppm. The table above summarizes the indicated increases in methane concentration due to sources on Manhattan island.

Given that these data subsets were for different survey paths on Manhattan, different reference zones off the island, and on different days, times of day and weather conditions, all effectively random, unplanned occurrences within the body of general methane survey data, the consistency of the indicated increase in methane concentration over Manhattan is actually impressive. In fact, the 99% confidence interval for the mean of the four days mean methane levels was ±0.068 ppm, or ±25%. Recall that the EPA/GRI[7] 90% confidence interval for cast iron pipelines was ±65%. For the purposes of evaluating the likely accuracy of the estimate of methane emissions on Manhattan Island, we will use ±25% as the likely accuracy of the data for increases in methane concentration in the air while passing over Manhattan Island. For data quality and field observational reasons, and to maintain a conservative approach, the 29 November data was regarded as most reliable and was used in the above calculation of annual methane flux to the atmosphere from Manhattan.

Weather data were obtained from online sources based on National Weather Service data or CCNY observations.[15] Wind speed is likely accurate to within 0.1 mph or 0.15 feet per second. Winds were moderate averaging 5.5 to 6.8 mph on the 4 survey days in the table above. The actual winds during the survey times in the table above tended to be above the average wind speed for the day. Since the data for 29 November was to be used in the calculation of the Manhattan methane flux rate, the wind speed for 4PM to 5PM on that day was estimated to be 8 mph and was the wind speed used. Potential error should not have been greater than 10% for the wind speed used in the calculation.

Wind direction was used for two purposes. One was identification of appropriate upwind methane reference areas and selection of an appropriate reference data subset within the full set of methane data. The other was to determine the length of the extent of Manhattan Island perpendicular to the direction of the wind. This length was used because the actual volume of air flowing over Manhattan should be related to the direction of the wind with respect to the greater N-S length and shorter E-W width of the island. If wind were blowing along the N-S length of the island, then, near the land surface, the band of air blowing onto and off the island would be about 2.5 miles wide. If the wind were blowing across the N-S length of the island, then the band of air would be closer 10 miles wide. So, at the land surface less air would be flowing onto and off the island for roughly N-S winds than for roughly E-W. It might seem this would cause some difficulty in that days with N or S winds would seem to have less air flowing over the island than days with E or W winds of the same speed. However, the height of the mixing layer increases with time over land compared to over water. So, this effect is probably in part compensated by related changes in the mixing layer height. In fact, on only one (09 December) of the four days did the wind run directly along the length of the island, and on that day the mixing layer height did increase substantially to a height of approximately 7200 feet.[15]

The width of the band of air blowing over the island was the length of the projection of the profile of Manhattan onto a line perpendicular to the wind direction, which we call the cross-wind length. On three of the four days the winds were nearly opposite in direction, from either the southwest or the northeast, so the cross-wind lengths of Manhattan were very similar except on 9 December when there was a compensating increase in mixing layer height. The cross-wind length of the island for any given wind direction can be relatively easily estimated to within a few percent using Google Earth.



A nighttime image showing the mixing layer over Berlin, Germany. Aerosol particles dispersed in the mixing layer cause light from below to be diffracted/reflected revealing the mixing layer as brighter and distinct from the clear (dark), uncontaminated air in the overlying layers of the atmosphere. Ralf Steikert http://userpage.fu-erlin.de/~kyba/images/night_boundary_layer.html

Another potential error source that might affect the calculation was the thickness or height of the mixing layer (see image above). Equipment capable of measuring the height of the top of the mixing layer is not common, but such equipment is in place in Manhattan.[15] Initially, the data was obtained in a graphic format and a 5% error was assumed due to graph reading inaccuracies. The graphs were read conservatively to assure the height of the mixing layer was not overestimated. The mixing layer occasionally has a somewhat diffuse upper boundary. This occurred at 4PM-5PM on 29 November. Only the mixing height that appeared to have the same or stronger composition (backscatter) as near the land surface was used. This predisposes the height of the mixing layer to underestimation as well as the resulting estimate of the actual methane flux, but, again, a conservative approach was preferred.[16]

Another potential source of error is the thoroughness of upward mixing of methane in the mixing layer at the time measurements were taken in the downwind sampling area, i.e., where air was leaving the island. Less than thorough mixing vertically throughout the mixing layer would seem likely if certain conditions were present. The land surface was relatively smooth, with few tall obstructions. The gas of concern was relatively dense and diffused slowly in the air. Winds were weak or inconsistent. The conditions during the relevant periods of the preliminary Manhattan methane survey were the opposite of these. Methane is lighter than air and diffuses rapidly through it, with a tendency to move upward. Winds were appreciable and consistent. With over 90 buildings more than 600 feet tall among many others of considerable height (see the image of the view from the "Top of the Rock" at the beginning of this report) the land surface of Manhattan is nearly the opposite of smooth. Further, the graphic representations of the ceilometer data for the relevant time periods indicated diffuse layers of air between the mixing layer and the overlying free atmosphere. Those diffuse layers were not included in the height of the mixing layer used in our calculations. At the time of this report, there did not appear to be reason to assume less than thorough vertical mixing of methane in the mixing layer. We anticipate opportunities to collect data that more directly address this possible source of error soon, and to revise our Manhattan methane emissions estimate in the near future.

Counter to a potential overestimate of methane emissions due to incomplete vertical mixing of methane in the mixing layer over Manhattan, there is also an unaccounted for potential loss of methane through the upper boundary of the mixing layer. Methane is only about half as dense as air, and is, therefore, strongly disposed to migrate upward in the atmosphere regardless of other conditions. It is, therefore, likely that at any given time a portion of the methane in the mixing layer is moving through the top of the mixing layer and on up into the atmosphere. Such "excessive vertical mixing" would not be accounted for in our calculations and would cause our emissions estimate to be low. We had no data on the thoroughness of vertical mixing of methane before the air in the mixing layer departs the island on the downwind side. We also have no data on what proportion of methane escapes out through the top of the mixing layer, but it seems unreasonable to expect that vertical methane loss

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[16] In the final stages of preparation of this report, the results of the application of two different mixing layer algorithms to the raw ceilometer data were provided courtesy of Mark Arend and Yonghau Wu of the City College of New York Optical Remote Sensing Lab and made available through the NOAA CREST NYCMetNet (http://nycmetnet.ccny.cuny.edu/). The average of the twelve results (6 time intervals X 2 algorithms) for 4PM-5PM 29 November time period was 0.815 kilometers, just 0.015 kilometers over our graphic estimate of 0.8 kilometers.

would be zero. It also seems likely that either incomplete or excessive mixing may be dominant in different areas within the downwind sampling area. Ultimately we assumed both processes were in effect, the effects of both countering each other in the overall data set. That is, we assumed that on average the vertical mixing was neither incomplete nor excessive. Again, we anticipate opportunities to collect data that will help us address this possible source of error, and hope to release those findings, and update our emissions estimate at the earliest practical date.

The potential error due to inadequate or excessive vertical excessive mixing in the mixing layer could not be estimated. At the time of preparation of this report, we had found only two publications on comparable measurement-based methane emissions from another large metropolitan area.[17,18] Both were for Krakow, Poland. The first of these, Kuc et al. (2003), estimated methane emissions were around 760 million cubic feet per year ($2.15 \text{ X } 10^{-7} \text{ m}^3 \text{ yr}^{-1}$) over the period 1996-1997. The later, Zimnoch et al. (2010), reported around 220 million cubic feet per year ($6.2 \text{ X } 10^{-6} \text{ m}^3 \text{ yr}^{-1}$) over the period 2005-2009, an apparent 3.5-fold decrease from the 1996-1997 estimate. In the intervening years the gas service operator in Krakow had undertaken a substantial gas infrastructure improvement program, presumably substantially reducing gas leakage. The population of Krakow is about 800,000[19], while Manhattan is very close to twice that, at 1.6 million[20]. The per capita gas consumption in Poland is around 16,000 cubic feet per year[21] and for New York is around 200,000 cubic feet per year[22]. Adjusting the 1996-1997 Krakow emissions for the higher population of Manhattan and New York per capita gas consumption rate, one obtains an emissions level of 19 billion cubic feet per year. The 2005-2009 Krakow emissions adjusted to Manhattan population and NY consumption rates becomes 5.5 billion cubic feet per year. We concluded

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[17] T. Kuc et al. 2003. Anthropogenic emissions of CO_2 and CH_4 in an urban environment. Appl. Energ. 75(3-4), 193-203.

[18] M. Zimnoch et al. 2010. Assessing surface fluxes of CO_2 and CH_4 in urban environment: a reconnaissance study in Krakow, Southern Poland. Tellus (2010), 62B, 573–580.

[19] http://www.krakow-info.com/people.htm

[20] http://www.nyc.gov/html/dcp/html/census/popcur.shtml

[21] http://www.indexmundi.com/map/?t=0&v=137000&r=eu&l=en (in cubic meters per year per capita, converted to cubic feet per year per capita)

[22] http://www.usnews.com/news/slideshows/the-10-states-that-use-the-least-energy-per-capita/11 (in BTU per capita in 2008, converted to cubic feet per capita per year)

our estimate of 8.6 billion cubic feet per year for Manhattan is reasonable in light of the estimates of Kuc (2003) and Zimnoch (2010) for Krakow.

In summary, among the measured data that were potential sources of error the 99% confidence interval of 25% relative for the methane concentration increase over Manhattan was the largest likely error. Each of the other potential sources of error were considered subject to errors of <10% relative. Further, when interpretation of data was required, those interpretations were conservative. It would seem reasonable at this point to hold that the estimated annual methane flux for Manhattan may contain an error of as much as ±25%.

Comparisons of the Estimated Emissions from Manhattan

An EPA/GRI[7]-Factors-Based Estimate

Applying the EPA/GRI[7] factors for pipe lengths and materials in the entire ConEd system[1], we arrived at an estimate of 915 million cubic feet as total gas leakage from the entire ConEd system of gas mains and service connection lines (services). Allowing an additional arbitrary 85,000,000 cubic feet for potential leakage from other ConEd gas infrastructure, we arrived at an estimated total methane leakage of around 1 billion cubic feet per year. Also, because soil conditions under Manhattan probably do not support optimal conditions for methane oxidation, we used the EPA/GRI[7] methane leakage factors instead of the methane emission factors. Use of the methane emission factors would have generated an even lower estimate of natural gas losses/ methane emissions.

An Average Long-Term LAUF Estimate

The ConEd ten-year average of LAUF gas (reported to PHMSA) was 2.2%. Even though the LAUF does not represent actual measured gas losses from the ConEd system, its preparation does involve metered gas flows albeit through many meters. Consequently, the LAUF might provide some indication of gas losses if inherent variability can be overcome, which can be accomplished by taking a long-term average. It should be kept in mind that 2.2% was the average ConEd LAUF over 10 years. As the average of 10 years this value is more reliable than the annual LAUF estimates used to calculate the average, but this greater reliability comes with costs. The average provides a more reliable estimate for leakage over times greater than one year, but may not be reliable for an individual year, say, a year impacted by a major storm. Also, leak detection and repair efforts are continuous. Use of a ten-year reporting period in order to have a reliable leakage rate would be useless with respect to annual or more frequent efforts to identify and control leakage. For present purposes of estimating total leakage, however, the 10-year average is the best value we can extract from the reported ConEd LAUF estimates. At 2.2% the ConEd LAUF for the entire ConEd gas system that handles about 300 billion scf/yr[1] would be 6.6 billion cubic feet of lost gas, or around 6.1 billion cubic feet of methane.

The GSI Estimate Based on Preliminary Ground-Level Methane Survey Data
The actual measured levels of methane in Manhattan and adjacent areas were used to develop an estimate of the likely rate of methane emissions from the natural gas system in Manhattan. The estimate did not include any ConEd gas distribution or service beyond the shorelines of Manhattan Island. The estimate used conservative criteria in selection of which data from outside (meteorological) sources would be used to generate the estimate. The resulting estimate of total emissions of methane (functionally losses of natural gas) was 8.6 billion cubic feet per year (≈9.2 billion cubic feet of natural gas).

This estimate is 1/3 larger than the 10-year average LAUF losses and nearly 10 times greater than the methane leakage estimates using the EPA/GRI[7] factors applied to the entire ConEd system of mains and services. Given that the primary function of reported values for LAUF gas is accounting reconciliation and equitable cost allocation, the error of 33% over the long term might be acceptable. However, given that the 33% higher estimate was based on methane-in-air measurements only in Manhattan, which accounts for only about one-third of the customers and 5% of the land area in the ConEd gas service territory, the question of how much more gas may be leaking in the remainder of the ConEd gas system service area stands unaddressed. Similarly, we leave for others to discuss the implications of the difference between our estimated methane emission rate for Manhattan and the reported LAUF gas from the entire ConEd system.

The difference between the annual Manhattan methane emission rate developed from GSI methane survey data and that generated by application of the EPA/GRI[7] pipelines leakage factors is more striking. If one were to assume that the EPA/GRI[7] data did account for distribution and service gas lines leakage within the accuracy given in that report (90% confidence interval was ±65% relative), then one would would expect that the entire ConEd system might have an emission rate up to 65% greater than the above mentioned estimate of 1 billion cubic feet per year based on the EPA/GRI[7] factors. That is, at the extreme upper limit proposed by EPA/GRI[7], the methane emissions for the entire ConEd system should be something around 1.65 billion cubic feet per year. Even if one uses this upper limit of an EPA/GRI[7]-based estimate, our estimate based on actual methane measurements in Manhattan alone is still almost 6 times greater.

Again, a Little Bit Matters

Returning to the issue of how much methane leakage is of practical concern, we need to put some perspective on the 8.6 billion cubic feet per year of methane emissions that we derived from our preliminary methane data for Manhattan. To do that we will need to make some assumptions. Our first assumption is pipeline natural gas is 93% methane (EPA/GRI[7]). Our second is that natural gas pipelines are the only sources of methane emissions on Manhattan. Our third assumption is there are no natural gas leaks from the ConEd system outside of Manhattan. This third assumption is obviously not true, but allows us to put 8.6 billion cubic feet into some perspective, while assuring that our conclusion is certainly conservative. Again, for clarification, Manhattan comprises about only 5% of the land area and accounts for only about 1/3 of the customers in the ConEd service territory.

Our measurements do not distinguish between methane sources. There could be methane sources in Manhattan other than the ConEd natural gas system. Given no data on this question at present, and based on GSI experience with methane surveys over fairly broad areas of the Northeast, our opinion is that it is unlikely methane from other sources would approach 10% of the emissions level indicated by our methane survey data in Manhattan. So, for purposes of this discussion the effects of the first two assumptions counter each other, plus ≈10% due to 93% methane content of pipeline natural gas, and minus ≈10% due to other potential methane sources in Manhattan.

Putting a number on the perspective for the estimated 8.6 billion cubic feet per year methane emissions from Manhattan now requires only comparison of that volume of gas to that handled by the ConEd system as a whole, i.e., ≈300 billion cubic feet per year. So our estimated annual methane emissions for Manhattan amount to only (100 X 8.6 billion / 300 billion =) 2.86%. Once again, why does this matter?

As mentioned back in the discussion of LAUF gas, this gas loss is actually 0.66% greater than the long-term average ConEd LAUF of 2.2%. With respect to hazards of explosive concentrations of methane in susceptible locations, this amount is probably not particularly important or informative. Though it seems reasonable to conclude such risks could increase proportionately with gas leakage (methane emissions), that would seem to matter little as the ConEd leak detection and management program has been running relatively effectively for decades with no real knowledge of what actual methane emissions have been. With respect to cost reconciliation and fair allocation, using the annual ConEd gas sales and services revenue of 1.5 billion dollars, 0.66% is 9.9 million dollars, consideration of which we will leave for ConEd, its customers, and

NYSDPS. With respect to the impacts of methane as a greenhouse gas, however, there is more to be said.

Methane is a potent greenhouse gas. A widely accepted minimum relative greenhouse gas strength of methane is 21 times greater than that of carbon dioxide over a 100-year time frame.[23] There have been complex and ongoing discussions about what the greenhouse equivalence of methane actually is, which the reader may want to consult.[24] Those discussions generally are resulting in incremental increases in the accepted value for methane greenhouse gas equivalence, but for this presentation we will use the simpler approach of using the lowest widely used greenhouse equivalence for methane. For convenience, we will further lower this by rounding it to 20 times greater than that of carbon dioxide. So, if methane is approximately 20 times stronger than carbon dioxide as a greenhouse gas, and if the natural gas upon reaching its destination is entirely burned to carbon dioxide (and water), then how important are gas (methane) leaks from the natural gas production and delivery system that delivered it?

We can restate that methane as a greenhouse gas is 20 times stronger than carbon dioxide by stating that it only takes 1/20 or 5% as much methane to cause as much atmospheric warming as a given quantity of carbon dioxide. If the natural gas arrives at its intended destination and is burned, it will form carbon dioxide (and water), so its original form (as methane) does not matter since it is now carbon dioxide. However, if only 5% of natural gas escapes as it moves from within the earth through the production, transport and delivery systems, that 5% will have as much GHG impact as the other 95% burned as fuel.

FINDINGS

The findings suggest the role of leakage from natural gas systems has a more substantial role in climate change than has been appreciated.[24] Apparently present provisions in state utility regulations allow gas companies to charge their customers for up to 2% (varies by state) of their handled gas volume as lost and unaccounted for gas (discussed earlier in this report). Depending on

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[23] http://epa.gov/climatechange/ghgemissions/gases/ch4.html, or, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html, among others.

[24] Alvarez, R. A., Pacala, S. W. Winebrake, J. J., Chameides, W. L. & Hamburg, S. P. Greater focus needed on methane leakage from natural gas infrastructure. Proc. Natl Acad. Sci. USA 109, 6435–6440 (2012).

the state, presumably such allowances apply to each sector of the gas system separately, i.e., production (gas wells), transportation (long distance pipelines), and distribution (gas utilities). In the end the methane emissions that affect the greenhouse gas impact of natural gas as fuel are the total methane emissions along the whole path the gas travels through the entire production-transport-distribution network. The infrastructure in each sector in that network can and does leak natural gas.

A 2.86% leakage of all the natural gas handled by ConEd in Manhattan alone leaves only 2.14% for the rest of the ConEd system, and the production and transport system feeding it, to leak collectively before total losses exceed the 5% level at which the greenhouse gas cost of using natural gas is effectively at least doubled. So far GSI efforts to gather data on volumes of gas lost by leakage or other processes in the natural gas system have indicated all such data are based on methods that are not founded in well-documented data on actual leaks, let alone actual measurements of leaks or field emissions. Some actual field data have recently been reported for production and early stage transport of shale gas. In the Denver-Julesberg Fossil Fuel Formation, largely in Weld County in northeast Colorado, emissions of methane were estimated at 2.3% to 7.7% of production.[25] Preliminary results from the Uinta Basin in Utah discussed at recent meetings of the American Geophysical Union indicated methane leakage in the field reached 9% of total production.[26] Even if the Marcellus shale gas fields planned to serve New York City release methane emissions at the lowest rate indicated by field data from northeast Colorado, and if that were added to just the GSI estimated methane emission for Manhattan alone, that would already put the total methane emission leak rate for Marcellus Shale gas delivered through the ConEd system at 5.16%. This leakage rate, which does not account for leakage from gas transmission lines to ConEd or from the rest of the ConEd system outside Manhattan, is already in excess of our simple calculation for the total leakage rate (5%) at which the leaked gas has as much potential climate impact as the burned gas. In fact, this leakage is well in excess of the total leakage rate of 3.2% at which other authors using more elaborate approaches have concluded that natural gas ceases to have a “clean fuel” advantage over coal for power production.[18]

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[25] Gabriel Petron et al. Hydrocarbon Emissions Characterization in the Colorado Front Range – A Pilot Study. National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Boulder, Colorado, USA. (Nature 482, 139–140; 2012)

[26] http://www.nature.com/news/methane-leaks-erode-green-credentials-of-natural-gas-1.12123#/ref-link-4

Caveats and Cautions Regarding the GSI Preliminary Estimate of the Manhattan Methane Emissions Rate

The GSI method (patent pending) used to estimate the Manhattan methane emissions rate from preliminary mobile methane survey data does not provide an estimate that is relative to natural background levels for natural areas in the region. It is difficult to imagine that there might even be an area anywhere in the vicinity of New York City where natural background methane emissions rates might be evaluated. The GSI approach was instead based on an alternate approach that could be evaluated because Manhattan is an island making physical boundaries of the Manhattan land surface emissions area relatively easy to define. Further, because of observations during the methane survey and analyses of the survey data, it became apparent that air arriving on the upwind and departing the downwind sides of the island at any given time necessarily provide a functional methane baseline and impacted air concentration level for the island. Hence, it is not necessary to know the natural methane baseline for the area or region, or even the surrounding waters, in order to calculate an emission rate for the island. Also, this approach eliminates any need to understand or attempt to correct off-island incoming air methane concentrations for methane sources within the geographical methane reference area since the only needed data is methane concentration in the incoming air.

The height of the mixing layer is important to the accuracy of the GSI approach to estimating area methane emissions based on ground level methane concentrations. Fortunately mixing height data is measured in Manhattan. However, the measurement used was collected at a single location not in the area where the departing air methane concentration data were collected. Nevertheless due to the mixing layer measurement location being relatively upwind from the air departure area it is more likely the mixing layer height used was too low rather than too high. Also, the measurement used was chosen to exclude diffuse zones at the upper edge of the mixing layer. Actual above ground and airborne measurements would be useful to assess variations of concentration of methane throughout the mixing layer.

There are potential and actual sources of methane in Manhattan other than the ConEd natural gas system. The GSI approach to estimating methane emissions cannot distinguish the contributions of various potential sources of methane to the overall methane emissions rate. One clearly distinguishable localized release of possible “sewer gas” was observed in the GSI Manhattan methane survey data collected at the outlet of a storm drain on the east side of the island. The elevated methane level was apparent, but not particularly high. How many other methane elevations might have been due to sewer gas or other potential, non-ConEd, methane sources, e.g., old fill areas, is not known. However, based on GSI experience in other urban and rural areas, the effects of using conservative allowances and assumptions wherever reasonable likely exceed the influence of landfill, sewer or other biologically generated methane in the GSI Manhattan preliminary methane emissions estimate. The relative importance of biogenic methane sources in Manhattan probably could be assessed using methane isotopic composition analysis. It is also worthwhile to note that just because gas is being released from a sewer or storm drain does not necessarily confirm that the gas is actually generated in the sewage or storm water and residues. Sewers and storm drains can also receive and transport gas leaked from gas pipes.

There is also potential for losses due to pirated or illegal gas taps, and post-metering losses at the consumer level. Again, such losses cannot be distinguished within the GSI Manhattan methane emissions estimate, but seem likely to be small in comparison to leakage from ConEd gas infrastructure and operations.

RECOMMENDATIONS

The estimated Manhattan methane emission rate presented in this report indicates the need for actual measurements of methane flux for urban, petroleum and gas field areas, etc. instead of estimates based on extrapolations of typically very limited and generally indirect data.

In Manhattan, additional ground level methane survey work seems needed to support more effective and rapid detection and identification of gas leaks, to determine areas where gas pipe is in need of general replacement or lining rather than stop-gap repairs. Additional ground level work is needed that is specifically designed to develop and refine the approach developed and presented in this report for rapid actual-measurement-based estimation of methane emissions. Additional supplementary work is needed to explore and refine the level of knowledge regarding the height of the mixing layer and methane distribution within it for Manhattan and other urban and non-urban settings.

The findings from this data analysis effort indicate there is need to re-evaluate:

- Methane emissions estimates and assumptions being used as the basis for global climate modeling and projections regarding the path and speed of climate change
- Plans and projections regarding short-term high-impact opportunities to reduce greenhouse gas emissions by focusing initially on methane emissions

associated with fossil fuel development, production, and utilization
- Regulation of the fossil fuel industry
- The actual economic and environmental costs of fossil fuel compared to alternative energy technologies over all time frames.

Our findings, based on actual measurements, necessarily raise doubts about the claimed value of natural gas as a "clean, bridge fuel" and call for further work to verify the reported findings and to begin to identify specific methane sources and improve natural gas leak prevention and management.

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We want to express our appreciation to the scientists and other colleagues who reviewed drafts and provided comments and suggestions during preparation of this report.

Appendix D

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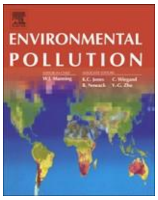

Rapid communication

Mapping urban pipeline leaks: Methane leaks across Boston

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Natural gas is the largest source of anthropogenic emissions of methane (CH_4) in the United States. To assess pipeline emissions across a major city, we mapped CH_4 leaks across all 785 road miles in the city of Boston using a cavity-ring-down mobile CH_4 analyzer. We identified 3356 CH_4 leaks with concentrations exceeding up to 15 times the global background level. Separately, we measured d$^{13}CH_4$ isotopic signatures from a subset of these leaks. The d$^{13}CH_4$ signatures (mean ¼ -42.8& ± 1.3& s.e.; n ¼ 32) strongly indicate a fossil fuel source rather than a biogenic source for most of the leaks; natural gas sampled across the city had average d$^{13}CH_4$ values of -36.8& (±0.7& s.e., n ¼ 10), whereas CH_4 collected from landfill sites, wetlands, and sewer systems had d$^{13}CH_4$ signatures w20& lighter (m ¼ -57.8&, ±1.6& s.e., n ¼ 8). Repairing leaky natural gas distribution systems will reduce greenhouse gas emissions, increase consumer health and safety, and save money.

1. Introduction

Methane (CH_4) is a greenhouse gas more potent molecule for molecule than carbon dioxide (Shindell et al., 2012). In the United States, leaks of CH_4 from natural gas extraction and pipeline transmission are the largest human-derived source of emissions (EPA, 2012). However, CH_4 is not just a potent greenhouse gas; it also influences air quality and consumer health. CH_4 reacts with NO_x to catalyze ozone formation in urban areas (West et al., 2006). Incidents involving transmission and distribution pipelines for natural gas in the U. S. cause an average of 17 fatalities, 68 injuries, and $133 M in property damage each year (PHMSA, 2012). A natural gas pipeline explosion in San Bruno, CA, for instance, killed eight people and destroyed 38 homes in 2010. Detecting and reducing pipeline leaks of CH_4 and other hydrocarbons in natural gas are critical for reducing greenhouse gas emissions, improving air quality and consumer safety, and saving consumers money (West et al., 2006; Han and Weng, 2011; Shindell et al., 2012; Alvarez et al., 2012).

To assess CH_4 emissions in a major urban metropolis, we mapped CH_4 emissions over the entire 785 centerline miles of Boston's streets. To evaluate the likely source of the street-level CH_4 emissions, we also measured the d^{13}CeCH$_4$ carbon isotope composition, which can differentiate between biogenic (e.g., landfill, wetland, sewer) and thermogenic (e.g., natural gas) sources (Schoell, 1980).

2. Materials and methods

We conducted 31 mobile surveys during the period 18 August, 2011e1 October, 2011, covering all 785 road miles within Boston's city limits. We measured CH_4 concentration ([CH_4], ppm) using a mobile Picarro G2301 Cavity Ring-Down Spectrometer equipped with an A0491 Mobile Plume Mapping Kit (Picarro, Inc, Santa Clara, CA). This instrument was factory-calibrated on 15 August 2011, immediately prior to use in this study, and follow-up tests of the analyzer were made during 11e21 August, 2012, comparing analyzer output to a National Oceanic and Atmospheric Administration (NOAA) primary standard tank. In both pre- and post-checks, the analyzer output was found to be within 2.7 parts per billion of known [CH_4] in standard tanks, three orders of magnitude below typical atmospheric concentrations. Spectrometer and mobile GPS data were recorded every 1.1 s. To correct for a short time lag between instantaneous GPS location and a delay in [CH_4] measurement due to inlet tube length (w3 m), we used an auxiliary pump to increase tubing flow throughput to within 5 cm of the analyzer inlet; we also adjusted the time stamp on the [CH_4] readings based on a 1-s delay observed between analyzer response to a standard CH_4 source that we injected into the instrument while driving, and the apparent GPS location. We also checked the GPS-based locations of leaks with dozens of street-level sampling to confirm specific leak locations and the estimated sampling delay. Air was sampled through a 3.0 um Zefluor filter and Teflon tubing placed w30 cm above road surfaces.

For our mobile survey data, we defined a "leak" as a unique, spatially contiguous group of [CH_4] observations, all values of which exceed a concentration threshold of 2.50 ppm. This was used as a threshold because it corresponded to the 90th

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percentile of the distribution of data from all road miles driven, and, relative to global background, is w37% above 2011 mean mixing ratios observed at Mauna Loa (NOAA, 2012).

Independently of mobile street sampling of CH$_4$, we measured d^{13}CH$_4$ from a subset of the leaks with a Picarro G2112i Cavity Ring-Down Spectrometer (Crosson, 2008). This instrument is calibrated monthly using isotopic standards from Isometric Instruments (Victoria, BC, Canada). The instrument was checked at least once daily to ensure analyzer output was within 1& of a tank of CH$_4$ with d^{13}CH$_4$ measured by a private lab (Isotech Labs, IL). Samples were collected in 1-L Tedlar sampling bags with valve and septa fittings, manufactured by Environmental Supply Company (Durham, NC). A Gas Sentry CGO-321 handheld gas detector (Bascom-Turner, MA) was used to identify the area of highest ambient [CH$_4$] at each site sampled for d^{13}CH$_4$. Sampling bags were pre-evacuated and filled at the area of highest ambient concentration at the sampling site using a hand pump. d^{13}CH$_4$ was analyzed using a Picarro G2112i with a sample hold time typically of a few days and always less than two weeks.

At a subset of sampling sites (n ¼ 12), we collected duplicate samples in glass vials to assess potential leaking or fractionation by the Tedlar sampling bags. We also sent duplicate samples from a different subset of sampling sites (n ¼ 5) to a private lab (Isotech Labs, IL) for independent d^{13}CH$_4$ analysis. These analyses suggest no significant fractionation or bias either from the sampling bags or the Picarro G2112i analyzer. Most samples were analyzed at less than the maximum hold time of two weeks, at which bag diffusion could account for a 1.2& drift in our measurements of d^{13}CH$_4$.

We compared d^{13}CH$_4$ of these locations with samples taken from area landfills, wetlands, and the Deer Island Water Treatment Facility. Sampling equipment and procedures, as well as laboratory analyses, for landfill and wetland sites were similar to those for d^{13}CH$_4$ sampling locations described above. Samples were collected from three capped, inactive landfills (there are currently no active landfills in the Boston area). At one former landfill site, samples were collected at approximately three-month intervals between September, 2011 and April, 2012. The d^{13}CH$_4$ signature of the landfill was consistent over this period (±3.4& s.e.). At all wetland sampling sites, a plastic chamber (10 cm x 25 cm x 5 cm) connected to a sampling tube was placed over the surface of exposed moist sediment or shallow (>5 cm) water. Sediment below the chamber was disturbed gently before drawing air samples from the headspace within the chamber. The sample from the Deer Island Treatment Facility was drawn from the headspace of a sample bottle of anaerobic sludge, collected onsite by Deer Island staff for daily monitoring of the facility's anaerobic sludge digesters.

3. Results and discussion

We identified 3356 CH$_4$ leaks (Figs. 1 and 2) exceeding 2.50 parts per million. Surface concentrations corresponding to these leaks ranged up to 28.6 ppm, 14-times above a surface background concentration of 2.07 ppm (the statistical mode of the entire concentration distribution). Across the city, 435 and 97 independent leaks exceeded 5 and 10 ppm, respectively.

Based on their d^{13}CH$_4$ signatures, the CH$_4$ leaks strongly resembled thermogenic rather than biogenic sources (Fig. 3). Samples of natural gas from the gateway pipelines to Boston and from other consumer outlets in the city were statistically indistinguishable, with an average d^{13}CH$_4$ signature of -36.8& (±0.7& s.e., n ¼ 10; & vs. Vienna Pee Dee Belemnite). In contrast, CH$_4$ collected from landfill sites, wetlands, and sewer systems reflected a greater fractionation from microbial activity and d^{13}CH$_4$ signatures w20& lighter. Biogenic values ranged from -53.1& to -64.5& (m ¼ -57.8&, ±1.6& s.e., n ¼ 8) for samples collected in four wetlands, three capped landfills, and the primary sewage facility for the city, Deer Island Sewage Treatment Plant, which had the heaviest sample observed for non-natural-gas sources (-53.1&). Our results for biogenic CH$_4$ carbon isotope signatures are consistent with other studies of the d^{13}CH$_4$ signature of CH$_4$ from landfills (Bergamaschi et al., 1998; Borjesson et al., 2001) and wetlands (Hornibrook et al., 2000).

Peaks of [CH$_4$] detected in the road surveys strongly reflected the signature of natural gas rather than biogenic sources (Table 1). The average d^{13}CH$_4$ value for peaks was -42.8& ± 1.3& (n ¼ 32), reflecting a dominant signal from natural gas, likely altered in some cases by minor fractionation of natural gas traveling through soils and by mixing with background air (d^{13}CH$_4$ ¼ -47&; Dlugokencky et al., 2011). A minority of samples had d^{13}CH$_4$ more negative than that of background air, reflecting apparent influence of biogenic CH$_4$. All 32 samples emitted a distinct odor of the mercaptan additive associated with natural gas, including those with a larger apparent biogenic influence on d^{13}CH$_4$.

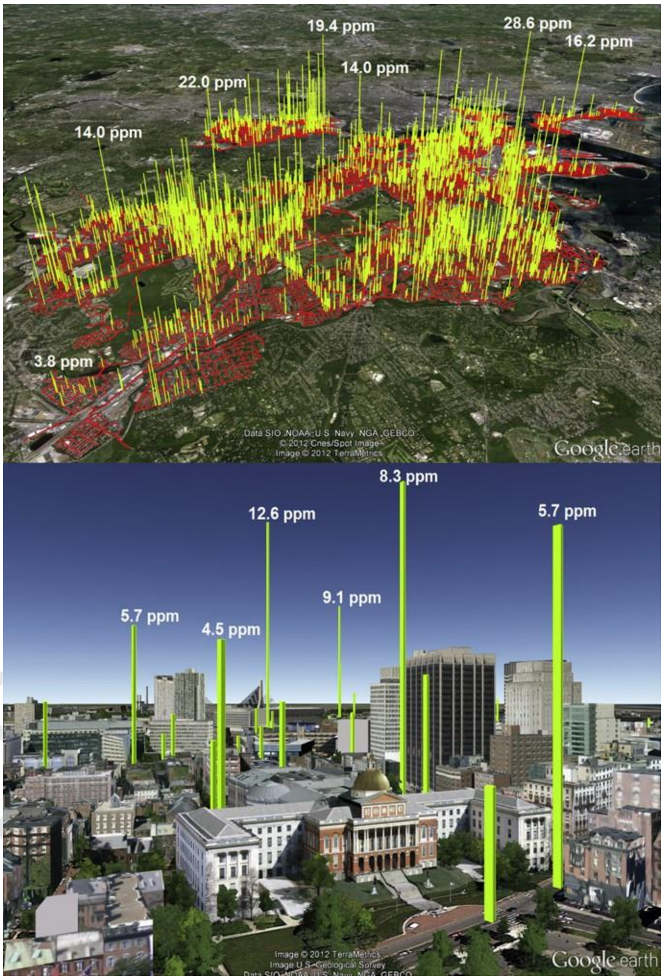

Fig. 1. Upper Panel: Methane leaks (3356 yellow spikes > 2.5 ppm) mapped on Boston's 785 road miles (red) surveyed in this study. Lower Panel: Leaks around Beacon Hill and the Massachusetts State House. Sample values of methane concentrations (ppm) are shown for each panel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

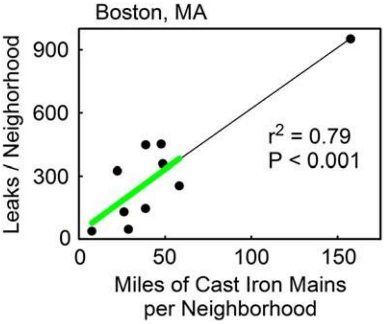

Fig. 2. Leak prevalence is associated with old cast iron pipes across ten Boston neighborhoods. (The combined line is the regression across all ten neighborhoods (P < 0.001); the green regression line [r^2 ¼ 0.34; P ¼ 0.08], which eliminates the influence of the leverage point [Dorchester neighborhood], has a slope and intercept indistinguishable (P > 0.10) from the combined regression.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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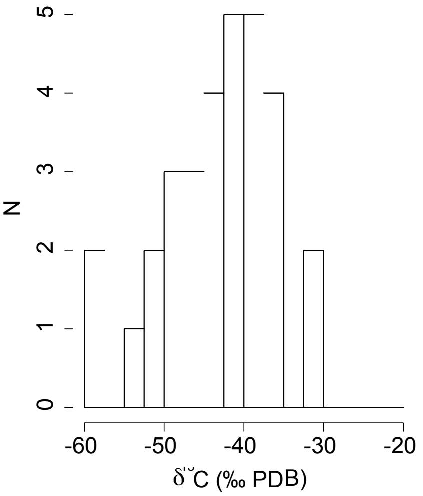

Fig. 3. d^{13}CH$_4$ of [CH$_4$] peaks detected in road surveys (n ¼ 32). Red lines represent means of thermogenic (-36.8&, ±0.7& s.e., n ¼ 10) and biogenic (-57.8&, ±1.6& s.e., n ¼ 8) sources, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Leaks across Boston (Fig. 1), were associated primarily with cast iron mains that were sometimes over a century old (Fig. 2). Across ten Boston neighborhoods, leak frequency was linearly related to number of miles of cast iron mains (r^2 ¼ 0.79, P < 0.001; Fig. 2), but only marginally to miles of non-cast-iron piping (r^2 ¼ 0.27; P ¼ 0.12, data not shown). Leak counts did not differ statistically by neighborhood or by socio-economic indicators for the neighborhoods obtained from the 2010 US Census (P > 0.1 for number of housing units and ethnicity) or the 2000 US Census (P > 0.1 for median income and poverty rate).

Table 1
Locations and isotopic values from discrete street leak samples.

Latitude	Longitude	d^{13}CH$_4$ (&PDB)
42.3654	-71.0612	-53.959
42.3439	-71.2628	-47.898
42.3493	-71.2265	-57.590
42.3583	-71.1749	-40.818
42.3411	-71.2440	-37.323
42.3543	-71.2441	-38.241
42.3559	-71.1898	-39.412
42.3513	-71.2092	-41.978
42.3515	-71.2081	-39.531
42.3614	-71.2314	-41.796
42.3426	-71.1012	-44.100
42.3443	-71.0949	-41.848
42.3328	-71.0761	-37.516
42.3360	-71.0738	-46.414
42.3441	-71.0673	-45.490
42.3303	-71.0569	-37.476
42.3409	-71.0542	-40.029
42.3524	-71.0445	-43.127
42.3799	-71.0272	-48.182
42.3722	-71.0361	-57.693
42.3785	-71.0681	-48.429
42.3730	-71.0632	-37.471
42.3593	-71.0629	-42.689
42.3584	-71.0644	-52.033
42.3546	-71.1271	-47.241
42.2943	-71.1891	-52.028
42.2793	-71.1514	-37.648
42.2887	-71.1428	-32.467
42.3285	-71.0792	-28.251
42.3215	-71.0692	-36.214
42.3269	-71.0796	-30.662
42.3553	-71.0573	-43.836
	Mean	-42.793
	Standard error	1.259

Reducing CH$_4$ leaks will promote safety and help save money. Although our study was not intended to assess explosion risks, we observed six locations where gas concentrations in manholes exceeded an explosion threshold of 4% [CH$_4$] at 20 °C (concentrations measured using a Gas Sentry CGO-321 handheld gas detector; Bascom-Turner, MA). Moreover, because CH$_4$, ethane (C$_2$H$_6$), and propane (C$_3$H$_8$) interact with NO$_x$ to catalyze ozone formation, reducing these hydrocarbon concentrations should help reduce urban ozone concentrations and respiratory and cardiopulmonary disease (West et al., 2006; Shindell et al., 2012). CH$_4$ is also a potent greenhouse gas, with an estimated 20-year global warming potential 72 times greater than CO$_2$ (Alvarez et al., 2012; Townsend-Small et al., 2012). Replacing failing natural gas mains will reduce greenhouse gas emissions, thereby providing an additional benefit to the fewer mercury, SO$_2$ and particulate emissions that natural-gas burning emits compared to coal (Shindell et al., 2012). Finally, leaks contribute to \$3.1 B of lost and unaccounted natural gas annually in the United States (EIA, 2012; 2005e2010 average).

Our ongoing and future research evaluates how surface [CH$_4$] values correspond to individual, and city-wide, urban leak rates and greenhouse-gas emissions. Two approaches to this question are useful: "bottom-up" chamber measurements taken on representative samples of individual leaks, and "top-down" atmospheric mass-balance estimates of the collective urban leak rate that exploit the known isotopic signature of natural gas versus that of biogenic sources and other fossil fuel sources. The instrumentation used in this study is well-suited for both approaches.

We propose that a coordinated campaign to map urban pipeline leaks around the world would benefit diverse stakeholders, including companies, municipalities, and consumers. Repairing the leaks will bring economic, environmental, and health benefits to all.

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References

Alvarez, R.A., Pacala, S.W., Winebrake, J.J., Chameides, W.L., Hamburg, S.P., 2012. Greater focus needed on methane leakage from natural gas infrastructure. Proceedings of the National Academy of Sciences U.S.A. 109, 6435e6440.

Bergamaschi, P., Lubina, C., Knigstedt, R., Fischer, H., Veltkamp, A.C., Zwaagstra, O., 1998. Stable isotopic signatures (d13C, dD) of methane from European landfill sites. Journal of Geophysical Research 103, 8251e8265.

Borjesson, G., Chanton, J., Svensson, B.H., 2001. Methane oxidation in two Swedish landfill covers measured with carbon-13 to carbon-12 isotope ratios. Journal of Environmental Quality 30, 369e376.

Crosson, E.R., 2008. A cavity ring-down analyzer for measuring atmospheric levels of methane, carbon dioxide, and water vapor. Applied Physics B: Lasers and Optics 3, 403e408.

Dlugokencky, E.J., Nisbet, E.G., Fisher, R., Lowry, D., 2011. Global atmospheric methane: budget, changes and dangers. Philosophical Transactions of the Royal Society A 369, 2058e2072.

Energy Information Administration (EIA), 2012. http://205.254.135.7/dnav/ng/ng_sum_lsum_dcu_nus_a.htm, http://205.254.135.7/naturalgas/annual/pdf/table_a01.pdf, http://205.254.135.7/naturalgas/annual/archive/2009/pdf/table_a01.pdf.

Environmental Protection Agency (EPA), 2012. http://epa.gov/methane/sources.html.

Please cite this article in press as: Phillips, N.G., et al., Mapping urban pipeline leaks: Methane leaks across Boston, Environmental Pollution (2012), http://dx.doi.org/10.1016/j.envpol.2012.11.003

Han, Z.Y., Weng, W.G., 2011. Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network. Journal of Hazardous Materials 189, 509e518.

Hornibrook, E.R.C., Longstaffe, F.J., Fyfe, W.F., 2000. Evolution of stable carbon isotope compositions for methane and carbon dioxide in freshwater wetlands and other anaerobic environments. Geochimica Cosmochimica Acta 64, 1013e1027.

National Oceanic and Atmospheric Administration, Annual Greenhouse Gas Index (AGGI), 2012. Earth System Research Laboratory, Global Monitoring Division. http://www.esrl.noaa.gov/gmd/aggi/ (accessed 10.09.12.).

Pipeline and Hazardous Materials Safety Administration (PHMSA), 2012. www.phmsa.dot.gov/pipeline/library/data-stats.

Schoell, M., 1980. The hydrogen and carbon isotopic composition of methane from natural gases of various origins. Geochimica Cosmochimica Acta 44, 649e661.

Shindell, D., Kuylenstierna, J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N.T.K., Milly, G., Williams, M., Demkine, V., Fowler, D., 2012. Simultaneously mitigating near-term climate change and improving human health and food security. Science 335, 183e189.

Townsend-Small, A., Tyler, S.C., Pataki, D.E., Xu, X., Christensen, L.E., 2012. Isotopic measurements of atmospheric methane in Los Angeles, California, USA: influence of “fugitive” fossil fuel emissions. Journal of Geophysical Research 117, D07308.

West, J.J., Fiore, A.M., Horowitz, L.W., Mauzerall, D.L., 2006. Global health benefits of mitigating ozone pollution with methane emission controls. Proceedings of the National Academy of Sciences U.S.A. 103, 3988e3993.

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Appendix E

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Quantifying sources of methane using light alkanes in the Los Angeles basin, California

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[1] Methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), and C_2–C_5 alkanes were measured throughout the Los Angeles (L.A.) basin in May and June 2010. We use these data to show that the emission ratios of CH_4/CO and CH_4/CO_2 in the L.A. basin are larger than expected from population-apportioned bottom-up state inventories, consistent with previously published work. We use experimentally determined CH_4/CO and CH_4/CO_2 emission ratios in combination with annual State of California CO and CO_2 inventories to derive a yearly emission rate of CH_4 to the L.A. basin. We further use the airborne measurements to directly derive CH_4 emission rates from dairy operations in Chino, and from the two largest landfills in the L.A. basin, and show these sources are accurately represented in the California Air Resources Board greenhouse gas inventory for CH_4. We then use measurements of C_2–C_5 alkanes to quantify the relative contribution of other CH_4 sources in the L.A. basin, with results differing from those of previous studies. The atmospheric data are consistent with the majority of CH_4 emissions in the region coming from fugitive losses from natural gas in pipelines and urban distribution systems and/or geologic seeps, as well as landfills and dairies. The local oil and gas industry also provides a significant source of CH_4 in the area. The addition of CH_4 emissions from natural gas pipelines and urban distribution systems and/or geologic seeps and from the local oil and gas industry is sufficient to account for the differences between the top-down and bottom-up CH_4 inventories identified in previously published work.

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1. Introduction

[2] In California, methane (CH_4) emissions are regulated by Assembly Bill 32, enacted into law as the California Global Warming Solutions Act of 2006, requiring the state's greenhouse gas (GHG) emissions in the year 2020 not to exceed 1990 emission levels. To this end, the California Air Resources Board (CARB) was tasked with compiling and verifying an inventory of GHG emissions for the state. Two published works [Wunch et al., 2009; Hsu et al., 2010] have concluded that atmospheric emissions of CH_4 in the Los Angeles (L.A.) area were greater than expected from a per capita apportionment of the statewide 2006 CARB GHG inventory and from a bottom-up accounting of CH_4 sources, respectively.

[3] Several recent works have estimated CH_4 emissions to the South Coast Air Basin (SoCAB; Figure 1a), which are summarized in Table 1. Wunch et al. [2009] used a Fourier transform infrared spectrometer at the Jet Propulsion Laboratory (JPL) in Pasadena, California to measure vertically integrated total column enhancement ratios of

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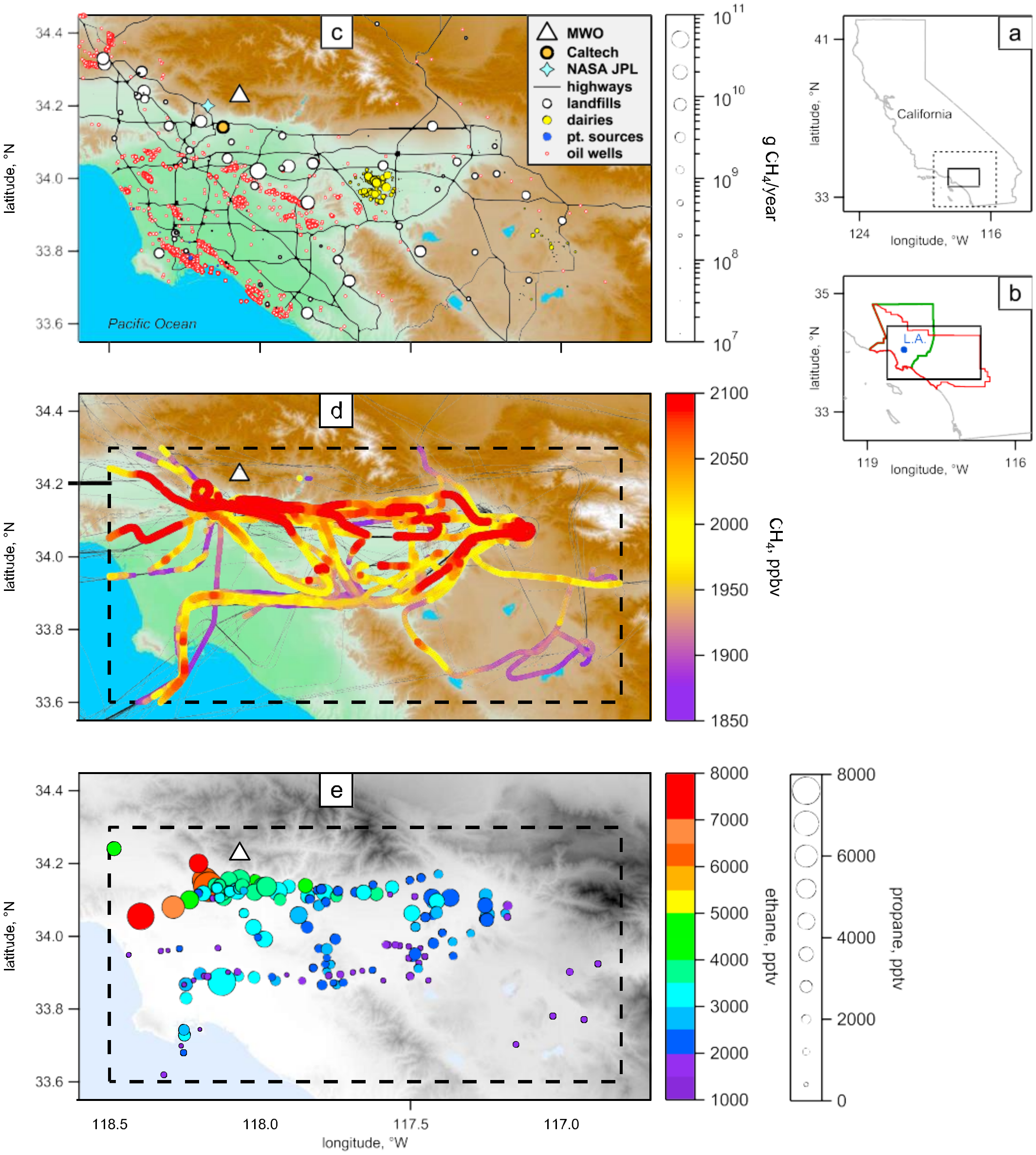

Figure 1. (a) Map of California. The dashed box shows the inset for Figure1b; the solid box shows the extent of the map boundaries for Figures 1c–1e. (b) Map of southern California showing the location of downtown L.A. (blue dot), the Los Angeles County boundary (green), the South Coast Air Basin boundary (red), and the extent of the map boundaries for Figures 1c–1e (black box). (c) Map of the L.A. region showing known sources of CH_4 in the L.A. basin. The white triangle shows the location of the Mount Wilson Observatory (MWO), where ground-based measurements were made by Hsu et al. [2010] and in this study. The light blue star shows the location of the Jet Propulsion Laboratory, where Wunch et al. [2009] made their measurements. The California Research at the Nexus of Air Quality and Climate Change (CalNex) Pasadena ground site was located on the California Institute of Technology (Caltech) campus, located at the orange-filled circle. Landfills (white circles) and CH_4 point sources (filled blue circles; negligibly small) are sized by emissions in the 2008 CARB greenhouse gas inventory. Dairies (filled yellow circles) are sized by the estimated emissions from the number of cows from Salas et al. [2008] multiplied by the 2009 CARB GHG inventory annual CH_4 emission per cow from enteric fermentation. (d) Same map of the Los Angeles region as in Figure 1c, with flight tracks from 16 daytime flights of the NOAA P-3 (thin black lines). CH_4 measurements from the daytime boundary layer are color-coded atop these tracks according to the legend to the right. (e) Locations of whole air samples in the L.A. basin are colored by ethane mixing ratio and sized by propane mixing ratio as indicated in the legends to the right. JPL, Jet Propulsion Laboratory.

Table 1. Summary of Past Studies Investigating CH_4 Emissions in the L.A. Basin

Study	Time of Study	Geographic Area	Percentage of California Population in Geographic Area	CH_4 Emission (Gg/yr)	Inventory Referenced	Bottom-up CH_4 Emission Inventory (Gg/yr)
Wunch et al. [2009]	August 2007 to June 2008	SoCAB	43%	400 ± 100	CARB CO 2007	260[b]
				600 ± 100	(CARB CO_2 2006 + EDGAR CO_2 2005)/2	
Hsu et al. [2010]	April 2007 to May 2008	L.A. County ∩ SoCAB	27%	200 ± 10	CARB CO 2007	140
Wennberg et al. [2012]	April 2007 to May 2008	SoCAB	43%	380[a] ± 100	CARB CO 2007	-
	June 2008	SoCAB	43%	470 ± 100	CARB CO 2008	-
	May 2010 to June 2010	SoCAB	43%	440 ± 100	CARB CO 2010	-

[a] Wennberg et al. [2012] recalculated the data reported by Hsu et al. [2010] to estimate a CH_4 emission from the entire SoCAB.

[b] Wunch et al. [2009] apportioned the statewide CARB GHG inventory for CH_4, less agriculture, and forestry emissions, by population.

CH_4 relative to CO and to CO_2. The observed column enhancement ratios, multiplied by CARB inventory values of CO for 2008 and an average of 2006 CARB GHG inventory and 2005 Emission Database for Global Atmospheric Research (EDGAR) for CO_2, were used to derive a lower limit to CH_4 emissions of 400 ± 100 Gg CH_4/yr (based on CO) or 600 ± 100 Gg CH_4/yr (based on CO_2) for the SoCAB. One reason for the discrepancy in their top-down analysis was that their observed CO/CO_2 enhancement ratio of 11 ± 2 ppb CO/ppm CO_2 was greater than the 8.6 ppb CO/ppm CO_2 calculated from the inventories. Wunch et al. [2009] contrasted these top-down assessments to a bottom-up estimate of 260 Gg CH_4/yr using the statewide 2006 CARB GHG inventory apportioned by population after removal of agricultural and forestry emissions, and concluded that 140–340 Gg CH_4/yr were not accounted for in the CARB CH_4 inventory for the SoCAB.

[4] Hsu et al. [2010] took a similar top-down approach and used observed atmospheric enhancement ratios of CH_4 to CO from in situ whole air samples taken at Mount Wilson (34.22°N, 118.06°W, 1770 m above sea level), scaled by the projected CARB CO inventory for 2008, to derive CH_4 emissions of 200 ± 10 Gg CH_4/yr for just the Los Angeles (L.A.) County (Figure 1b) portion of the SoCAB (L.A. County ∩ SoCAB). They used methods prescribed by the Intergovernmental Panel on Climate Change (IPCC) to create the CARB GHG inventory and reached a bottom-up estimate of 140 Gg CH_4/yr, or 60 Gg less than their top-down calculation for the L.A. County portion of the SoCAB. Hsu et al. [2010] used higher spatial resolution emissions data from CARB to construct their bottom-up inventory and therefore did not have to rely on population apportionment methods used by Wunch et al. [2009].

[5] The difference between the top-down CH_4 emissions reported by Wunch et al. [2009] and by Hsu et al. [2010] (400 Gg and 200 Gg, respectively, both based on the CARB CO inventory) are in part due to the different geographic areas for which they calculate CH_4 emissions, and in part due to differences in observed CH_4/CO enhancements between these two studies: 0.66 ± 0.12 mol/mol for Wunch et al. [2009] [Wennberg et al., 2012] and 0.52 ± 0.02 mol/mol for Hsu et al. [2010]. Both works suggested that fugitive losses of natural gas (NG) could be the source of the CH_4 missing from the bottom-up inventories.

[6] More recently, Townsend-Small et al. [2012] analyzed stable CH_4 isotope ratios in atmospheric samples taken at Mount Wilson and elsewhere in the western L.A. basin and showed they were consistent with isotope ratios in natural gas sources. Wennberg et al. [2012] used the different atmospheric ethane/CH_4 enhancement ratios observed from research aircraft during the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) field project in 2008 and the California Research at the Nexus of Air Quality and Climate Change (CalNex) field project [Ryerson, 2013] in 2010 to estimate an upper limit of 400 Gg CH_4/yr from natural gas leakage in the SoCAB. Further, their top-down analysis resulted in a calculated total emission of 440 Gg CH_4/yr in the SoCAB. Wennberg et al. [2012] also recalculated the data used by Hsu et al. [2010] to derive CH_4 emissions for the entire SoCAB and calculated a SoCAB CH_4 emission from 2008 using data from ARCTAS. The results are summarized in Table 1.

[7] Here we use ambient measurements in the SoCAB taken in May and June 2010 aboard the National Oceanic and Atmospheric Administration (NOAA) P-3 research aircraft during the CalNex field study to derive CH_4 emissions from the SoCAB using methods different from Wennberg et al. [2012]. We further examine CH_4 emissions from landfills and dairy farms in the SoCAB identified in the bottom-up CH_4 inventories reported by Hsu et al. [2010] and Wennberg et al. [2012]. We then expand on these previous studies by examining light alkane emissions from Los Angeles area data sets. In addition to CH_4 and ethane, we examine propane, n- and i-butane, and n- and i-pentane measurements to derive emissions of each of these light alkanes in the SoCAB, and use them in a system of linear equations to further quantify the source apportionment of CH_4 in the L.A. basin.

2. Measurements

[8] We use trace gas measurements from a subset of platforms and sites from the CalNex field study. The NOAA P-3 research aircraft flew all or parts of 16 daytime flights in and around the L.A. basin. Two independent measurements of CH_4 and CO_2 were made aboard the aircraft by wavelength-scanned cavity ring-down spectroscopy (WS-CRDS; Picarro 1301 m) [Peischl et al., 2012], and by quantum cascade laser direct absorption spectroscopy (QCLS) [Kort et al., 2011].

Imprecision of the 1 Hz Picarro CH_4 measurement is ±1.4 ppbv (all uncertainties herein are 1-σ), and inaccuracy is estimated at ±1.2 ppbv. Imprecision of the 1 Hz QCLS CH_4 measurement is ±1 ppbv, and inaccuracy is estimated at ±15 ppbv. Imprecision of the 1 Hz Picarro CO_2 measurement is ±0.14 ppmv, and inaccuracy is estimated at ±0.12 ppmv. Imprecision of the 1 Hz QCLS CO_2 measurement is ±0.05 ppmv, and inaccuracy is estimated at ±0.10 ppmv. All CH_4 and CO_2 measurements are reported as dry air mole fractions. For this work, CH_4 and CO_2 data from the Picarro instrument are used, and QCLS CH_4 data from May 8 are used when the Picarro instrument was not operating. The 1 Hz CO data used in this analysis were measured by vacuum ultraviolet fluorescence spectroscopy [Holloway et al., 2000]. Imprecision of the 1 Hz CO data is ±1 ppbv; inaccuracy is estimated at ±5%. C_2 to C_5 alkanes, and their structural isomers, were measured in whole air samples [Colman et al., 2001], periodically filled during flight. Imprecision of these alkane measurements is ±5%; inaccuracies are estimated at ±10%. Wind measurements were derived from various sensors aboard the NOAA P-3; the uncertainty of the 1 Hz wind speed is estimated to be ±1 m/s. Sensors aboard the NOAA P-3 also measured relative humidity, ambient temperature, and potential temperature with an estimated 1 Hz uncertainty of ±0.5 °C, ±0.5 °C, and ±0.5 K, respectively.

[9] At the CalNex Pasadena ground site, located on the California Institute of Technology (Caltech) campus, measurements of C_2–C_5 alkanes were made by a gas chromatograph-mass spectrometer on 5 min integrated samples taken every half hour [Gilman et al., 2010]. Imprecision of these measurements are ±8% for ethane and ±6% for propane; inaccuracy is estimated at ±15% for each. Data from the ground site were taken between 15 May and 15 June 2010. CH_4 was not measured at the Pasadena ground site.

[10] Additionally, whole-air flask samples were taken twice daily at the Mount Wilson Observatory (MWO) for most days during May and June 2010 and analyzed for a variety of trace gas species, including CH_4, CO_2, CO, and hydrocarbons [Dlugokencky et al., 2011; Conway et al., 2011; Novelli and Masarie, 2010]. Imprecision of the CH_4 measurement is ±1 ppb; imprecision of the CO_2 measurement is ±0.1 ppm; imprecision of the CO measurement is ±1 ppbv, and inaccuracy of the CO measurement is estimated to be ±5%.

[11] We also analyze alkane data from whole air samples taken in the L.A. basin prior to 2010. Ethane and propane were measured in whole air samples taken on four flights in L.A. aboard an instrumented National Aeronautics and Space Administration (NASA) DC-8 research aircraft during ARCTAS in June 2008 [Simpson et al., 2010]. Ethane and propane were also measured on one flight in L.A. aboard the NOAA P-3 during the Intercontinental Transport and Chemical Transformation (ITCT) study in May 2002 [Schauffler et al., 1999].

3. Methods

[12] To ensure sampling from the L.A. basin, we consider aircraft data collected between 33.6 and 34.3°N latitude and 118.5 and 116.8°W longitude (Figure 1d, dashed box) in the following analysis. Aircraft data were further limited to samples taken between 1000 and 1700 PST, between 200 and 800 m above ground, and below 1400 m above sea level, to ensure daytime sampling was within the well-mixed boundary layer, which averaged 1000 ± 300 m above ground level for the daytime L.A. flights [Neuman et al., 2012]. Ground-based measurements at Pasadena were retained between 1000 and 1700 PST to ensure sampling of a well-mixed daytime boundary layer. For MWO measurements, afternoon samples, which typically occurred between 1400 and 1500 PST, were retained to capture upslope transportation from the L.A. basin [Hsu et al., 2010]. Linear fits to the data presented below are orthogonal distance regressions [Boggs et al., 1989] weighted by instrument imprecision (weighted orthogonal distance regression (ODR)). The total uncertainty in the fitted slope is calculated by quadrature addition of the fit uncertainty and the measurement uncertainties.

[13] For flux determinations, crosswind transects were flown downwind of known point sources. Enhancements of CH_4 above background levels were integrated along the flight track, and a flux was calculated using the following equation:

$$\text{flux} = v\cos(\alpha)\int_{z_0}^{z_1} n(z)dz\int_{-y}^{y} X_m(y)dy \qquad (1)$$

where $v\cos(\alpha)$ is the component of the average wind velocity normal to the flight track, n is the number density of the atmosphere, z_0 is the ground level, z_1 is the estimated boundary layer height, and X_m is the measured mixing ratio enhancement above the local background along the flight track [White et al., 1976; Trainer et al., 1995; Ryerson et al., 1998; Nowak et al., 2012]. Boundary layer heights are estimated from vertical profiles of relative humidity, ambient temperature, and potential temperature made prior to and after the crosswind transects. We assume the plume is vertically homogeneous within the mixed layer at the point of measurement, and the wind velocity is constant between emission and measurement. We estimate the uncertainty in these assumptions, combined with the uncertainties of the wind speed, wind direction, temperature, and integrated atmospheric enhancements to be ±50% for the plumes studied here [Nowak et al., 2012]. Weighted averages of the fluxes are calculated following Taylor [1997]. When calculating the CH_4 flux from dairies, CH_4 variability immediately upwind of the dairies is sufficiently large to complicate interpolation from the downwind local background. To account for this, we take the weighted ODR slope of CH_4/CO immediately upwind, multiply this ratio by the measured CO downwind of the dairies, and integrate the plume CH_4 enhancement calculated from CO ($CO \times [CH_4/CO]_{upwind}$), similar to the integrations performed by Nowak et al. [2012]. This assumes the dairies emit a negligible amount of CO.

[14] As with previously published works [Wunch et al., 2009; Hsu et al., 2010; Wennberg et al., 2012], we estimate total CH_4 emissions in the SoCAB by multiplying enhancement ratios of CH_4 to CO and CO_2 by inventory estimates of CO and CO_2 for that region:

$$E_{CH_4} = \left(\frac{CH_4}{X}\right)_{\text{ODR slope}} \times \left(\frac{MW_{CH_4}}{MW_X}\right) \times E_X \qquad (2)$$

where E_{CH4} is the emission of CH_4, X is either CO or CO_2, MW is the molecular weight, and E_X is the inventory

Table 2. Inventories Used in Current Analysis

Emission	Inventory	Year	Geographic Area
180 Tg CO_2/yr	CARB GHG[a]	2009	SoCAB[c]
979 Gg CO/yr	CARB[b]	2010	SoCAB
301 Gg CH_4/yr	CARB GHG[a]	2009	SoCAB[c]

[a] 2009 CARB CO_2 and CH_4 emissions (http://www.arb.ca.gov/cc/inventory/data/data.htm).

[b] projected 2010 CARB CO emissions (http://www.arb.ca.gov/app/emsinv/fcemssumcat2009.php).

[c] statewide inventory apportioned by SoCAB population.

emission value of either CO or CO_2. Although not necessarily emitted from the same sources, we assume emissions of CH_4, CO, and CO_2 are well-mixed by the time they are sampled from the NOAA P-3.

[15] We use the following latest available inventories for our analysis below: the 2010 CARB emissions inventory for CO projected from the base-year 2008 inventory (http://www.arb.ca.gov/app/emsinv/fcemssumcat2009.php) and the 2009 CARB GHG inventory (http://www.arb.ca.gov/cc/inventory/data/data.htm). Both inventories were accessed in November 2012.

[16] CARB projects the total 2010 annually averaged CO emissions in the SoCAB at 979 Gg CO/yr (Table 2). We use the annually averaged CARB inventory that excludes biomass burning CO emissions because no known biomass burning events were observed in the L.A. basin during CalNex. This estimate is 4% less than the summertime CO inventory without biomass burning emissions, and approximately 6% less than the annually averaged CO inventory including biomass burning emissions used by Wennberg et al. [2012]. To estimate 2010 CH_4 emissions in the SoCAB using the 2009 CARB GHG inventory, we follow the method used by Wunch et al. [2009] and take the total statewide emission of 1525 Gg CH_4/yr, less agricultural and forestry CH_4 emissions of 898 Gg CH_4/yr, then apportion the remainder by population. In 2010, the SoCAB comprised 43% of California's population (http://www.arb.ca.gov/app/emsinv/trends/ems_trends.php). However, unlike Wunch et al. [2009], we include SoCAB dairy emissions of 31.6 Gg CH_4/yr, which are calculated in section 4.3 below. Therefore, we attribute a total of 301 Gg CH_4/yr to the SoCAB based on the 2009 CARB GHG inventory (Table 2).

[17] According to CARB's mobile source emission inventory for the Los Angeles County portion of the SoCAB (http://www.arb.ca.gov/jpub/webapp//EMFAC2011WebApp/emsSelectionPage_1.jsp), mobile source CO_2 emissions remained essentially unchanged between 2009 and 2010 (39.94 versus 39.95 Tg CO_2/yr). Additionally, the statewide CARB GHG inventory for CO_2, with out-of-state electricity generation emissions removed, decreased by less than 2% between 2008 and 2009. Therefore, we assume errors due to sampling year are negligible in examining the CO_2 emission inventories in the SoCAB from 2009 to 2010. To estimate 2010 CO_2 emissions in the SoCAB using the 2009 CARB GHG inventory, we take the total statewide emission of 465.7 Tg CO_2/yr, subtract out-of-state electricity generation of 47.9 Tg CO_2/yr, and then apportion the remainder by population. We therefore attribute 180 Tg CO_2/yr to the SoCAB using the 2009 CARB GHG inventory (Table 2). We do not compare to the Vulcan CO_2 inventory [Gurney et al., 2009] because at present, it is only available for the 2002 reporting year.

4. Results and Discussion

4.1. Total Derived Emission of CH_4 in L.A. and Comparison to Inventories

[18] In this section, we use P-3 measurements of CH_4, CO, and CO_2 to calculate enhancement ratios representative of the integrated emissions from the L.A. basin. We then use tabulated CO and CO_2 emissions taken from the CARB inventories to derive total CH_4 emissions based on enhancement ratios observed in CalNex and compare to earlier estimates of total CH_4 emissions in L.A.

[19] Figure 1c shows known stationary sources of CH_4 in the L.A. area, which include landfills, dairies, wastewater treatment facilities, and oil fields, as well as the location of measurement sites used in this study. Dairy sources are sized by estimated CH_4 emissions from enteric fermentation, as explained in section 4.3. Landfills are sized by CH_4 emissions from the 2008 CARB GHG inventory (L. Hunsaker, personal communication, 2011). Point sources are sized by 2009 CARB individual facility CH_4 emissions (https://ghgreport.arb.ca.gov/eats/carb/index.cfm) but do not stand out in the map due to their low CH_4 emissions relative to the landfills and dairies. Figure 1d shows the locations of daytime boundary-layer CH_4 data from the P-3, colored by observed mixing ratio, that were retained for the analysis as described previously. The largest concentrations of CH_4 were typically encountered along the mountains at the north edge of the L.A. basin, likely driven by transport of air within the basin, as typical daytime winds in the L.A. basin were from the west and southwest during May and June 2010 [Washenfelder et al., 2011]. CalNex CH_4 data are plotted against observed CO in Figure 2a. Weighted ODR fits to these data resulted in derived enhancement ratios of 0.74 ± 0.04 and 0.68 ± 0.03 ppbv CH_4/ppbv CO from the NOAA P-3 and MWO, respectively. We note that the same CH_4/CO enhancement ratio of 0.74 ± 0.03 was reported by Wennberg et al. [2012] using the CalNex P-3 data with different selection criteria. We include box and whisker plots in Figure 2a to show that the weighted ODR fit to the data is insensitive to the relatively few data points of higher CH_4. The ratio calculated from the CARB inventory (Table 2) is 0.54 ppb CH_4/ppb CO and is displayed for comparison.

[20] CalNex CH_4 data are plotted against observed CO_2 in Figure 2b. The slope from a weighted ODR of P-3 data is 6.70 ± 0.01 ppb CH_4/ppm CO_2 and of MWO data is 6.60 ± 0.04 ppb CH_4/ppm CO_2. The ratio of the CARB inventories from Table 2 is 4.64 ppb CH_4/ppm CO_2 and is displayed for comparison. In this case, because CH_4 and CO_2 are measured with high precision and accuracy, the largest uncertainties in interpreting the slope as an emissions ratio are likely determined by the extent of mixing of emissions from different sources within the Los Angeles air shed. Similarly, Figure 2c shows a correlation plot of CO against CO_2. The slope from a weighted ODR of P-3 data is 9.4 ± 0.5 ppb CO/ppm CO_2 and of MWO data is 10.4 ± 0.5 ppb CO/ppm CO_2. The ratio of the CARB inventories from Table 2 is 8.5 ppb CO/ppm CO_2 and is plotted

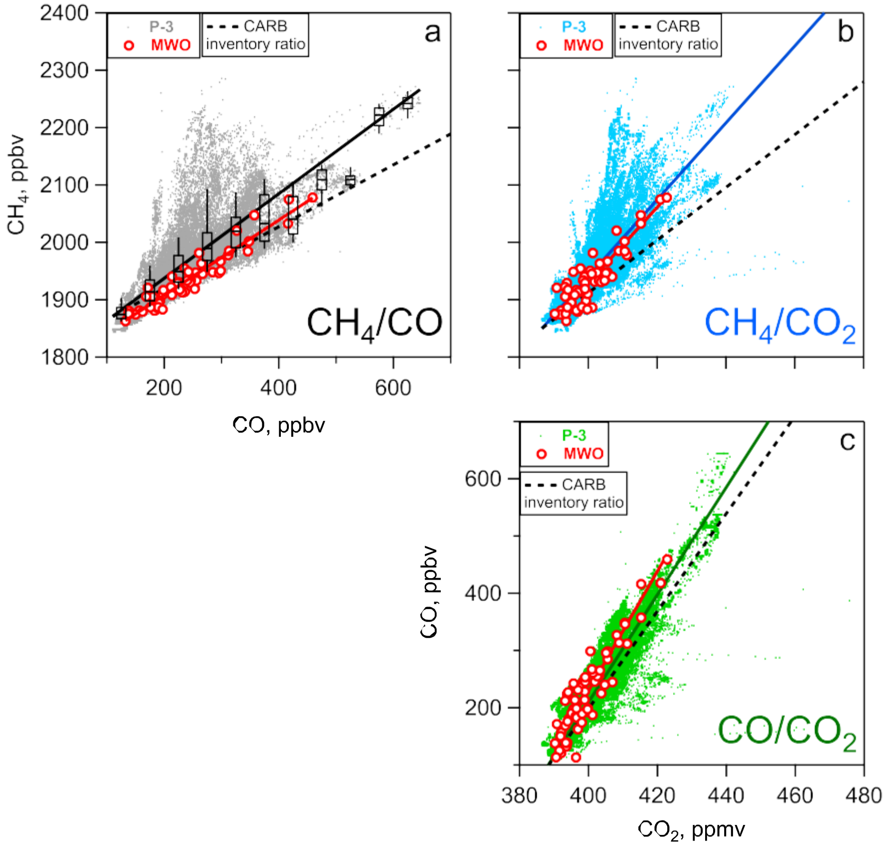

Figure 2. Scatter plots of CH_4, CO_2, and CO from all 1 s data points along flight track highlighted in Figure 1. Dots are from the NOAA P-3, while red circles are from NOAA GMD flask samples taken at the Mount Wilson Observatory during CalNex. Weighted ODRs (solid lines) result in slopes of (a) 0.74 ± 0.04 and 0.68 ± 0.04 ppb CH_4/ppb CO; (b) 6.70 ± 0.01 and 6.60 ± 0.04 ppb CH_4/ppm CO_2; and (c) 9.4 ± 0.5 and 10.4 ± 0.5 ppb CO/ppm CO_2 from the NOAA P-3 and Mount Wilson Observatory, respectively. The black dotted lines represent molar ratios of the CARB inventories listed in Table 2: CH_4:CO = 0.54, CH_4:CO_2 = 4.64×10^{-3}, and CO:CO_2 = 8.5×10^{-3}, where the background values used are the same as those determined from the fitted slopes. Also, plotted in Figure 2a are boxes (25th–75th percentiles), whiskers (10th–90th percentiles), and the median (horizontal line) for distributions of CH_4 data calculated for 50 ppbv wide bins from the NOAA P-3 CO data.

for comparison. We estimate a ±7.5% uncertainty in each of the CARB CO and CO_2 inventories, which is sufficient to explain the difference between the CO/CO_2 enhancement ratio measured from the NOAA P-3 and the ratio calculated from the CARB inventories. Quantitative agreement between emission ratios derived from P-3 and MWO data (Figures 2a–2c) is likely due to the fact that the transport within the basin was driven by the land-sea breeze, meaning typical daytime winds in the Pasadena area near Mount Wilson were from the southwest [Washenfelder et al., 2011]. This transport, and the highest values of CH_4 and CO_2 in the P-3 data that are not seen at MWO (Figures 2a and 2b), also suggests that MWO preferentially samples the western part of the L.A. basin [Hsu et al., 2010]. We therefore use enhancement ratios determined from the NOAA P-3 data to derive CH_4 emissions from the entire basin.

[21] We note that the ratio of the latest CARB CO and CO_2 inventories (Table 2) are in better agreement with ambient enhancement ratios in the CalNex data than was the case for Wunch et al. [2009]. This is likely due to either improved CARB inventories, the present use of a basin-wide data set to determine basin-wide emission ratios, or both.

[22] With the slopes and inventory values quantified, we next derive a CH_4 emission using equation (2). Using the CH_4/CO slope derived from the weighted ODR fit to the 2010 NOAA P-3 data and the projected 2010 CARB annually averaged CO emission inventory in equation (2) yields an estimated SoCAB emission of 410 ± 40 Gg CH_4/yr. The stated uncertainty is the quadrature propagation of the measurement uncertainty, errors on the slope of the ODR fit to P-3 data, and an estimated uncertainty in the CARB CO inventory. We note our derived emission of 410 ± 40 Gg CH_4/yr is similar to that derived from the P-3 data by Wennberg et al. [2012], which was 440 ± 100 Gg CH_4/yr using different selection criteria. It is further consistent with the emission derived by Wunch et al. [2009] of 400 ± 100 Gg CH_4/yr, which assumed a CARB CO inventory uncertainty of 15%. We also determine CH_4 emissions using estimates of CO_2 emissions in the SoCAB. P-3 measurements of the CH_4/CO_2 enhancement ratio observed during CalNex and SoCAB CO_2 emissions inferred from

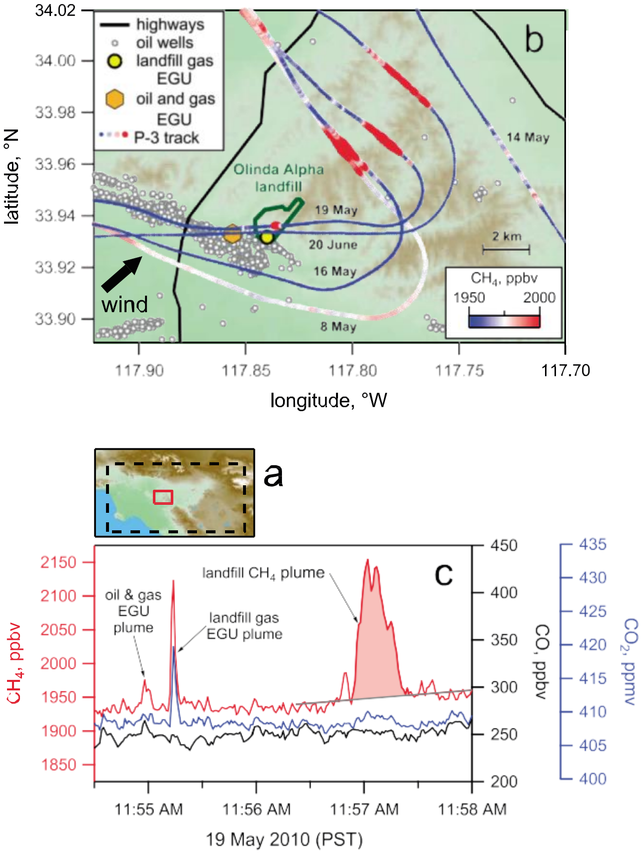

Figure 3. (a) The map from Figures 1c to 1e shows the inset for Figure 3b in red. (b) Five downwind transects, sized, and colored by CH_4 mixing ratio, showing enhancements in CH_4 downwind of the Olinda Alpha landfill (green outline). Winds were from the southwest, except on 14 May, when they were from the west and southwest. (c) Example of integration of the CH_4 plume from the 19 May flight. The filled pink area is integrated above the surrounding background (gray line). The upwind transect on this day passed downwind of two power plant (Electric Generating Unit (EGU)) plumes.

the 2009 CARB GHG inventory result in a derived CH_4 emission rate of 440 ± 30 Gg CH_4/yr, with the stated uncertainties determined by quadrature propagation of the measurement uncertainty, errors on the slope of the ODR fit to P-3 data, and an estimated uncertainty in the CARB CO_2 inventory. This value, based on the CO_2 inventory, is consistent with that derived using P-3 measurements and the CO inventory, further supporting both our assessment of uncertainties in the CARB CO and CO_2 inventories, and our assumption of sampling well-mixed emissions in the SoCAB, since any outlying CH_4 data do not affect the overall emission estimates significantly.

[23] The derived 2010 top-down SoCAB CH_4 emission of 410 and 440 Gg CH_4/yr reported here using the CARB CO or CO_2 inventories, respectively, are in quantitative agreement, in contrast to that reported for 2008 [Wunch et al., 2009]. The 2010 estimates are a factor of 1.35 to 1.45 greater than the modified population-apportioned 2009 CARB GHG inventory value of 301 Gg CH_4/yr (Table 2). A concurrent inverse modeling study by Brioude et al. [2012] has found no statistical difference between the total SoCAB CO emissions reported by CARB for 2010 and a top-down approach that estimated CO emissions in the SoCAB region using the same CO measurements used in this paper. For this reason, and for consistency with published works [Wunch et al., 2009; Hsu et al., 2010; Wennberg et al., 2012], we use 410 ± 40 Gg CH_4/yr from the top-down CH_4 assessment based on 2010 P-3 measured CH_4/CO enhancement ratios and the CARB CO inventory for the remainder of our analysis.

4.2. Methane Emissions From L.A. Basin Landfills

[24] Landfills are the largest nonfossil fuel CH_4 emission source in the bottom-up inventories compiled by Hsu et al. [2010] and by Wennberg et al. [2012], but these two studies disagree on the magnitude of this source. Hsu et al. [2010] estimated annual emissions from landfills totaled 90 Gg CH_4/yr from the Los Angeles County portion of the South Coast Air Basin. Wennberg et al. [2012] reported landfill emissions of just 86 Gg CH_4/yr for the entire South Coast Air Basin. However, that number is too low due to an error in their gridded landfill emissions inventory (P. Wennberg, personal communication, 2012) and is discarded in the following analysis.

[25] In the CARB GHG inventory, CH_4 emissions are calculated for individual landfills using methods prescribed by the IPCC and summed over all landfills to estimate a statewide total. Annual CH_4 emission values for individual landfills were obtained directly from CARB (L. Hunsaker, personal communication, 2011) to facilitate direct comparison to the P-3 data from CalNex. We use the P-3 data to calculate emissions from two of the largest CH_4-emitting landfills in the statewide GHG inventory, both of which are located in the SoCAB.

[26] The first landfill results we examine are from the Olinda Alpha landfill (33.934°N, 117.841°W) in Brea, Orange County, California. The NOAA P-3 flew five daytime boundary-layer transects on five different days downwind of this landfill (Figure 3), and a CH_4 emission flux was determined for each transect using equation (1). The results are summarized in Table 3. For the three transects when both the WS-CRDS and QCLS CH_4 instruments were sampling ambient air, flux determinations using these independent CH_4 measurements agreed within

Table 3. Landfill Emission Fluxes Determined Aboard the NOAA P-3 in 2010 From Downwind Plume Transects

Landfill	Transect Date	Flux (10^{25} molecules/s)	Flux (Gg/yr)	2008 CARB GHG Inventory^a (Gg/yr)
Olinda Alpha	8 May	1.13	9.5	11.0
	14 May	1.45	12.2	
	16 May	1.74	14.6	
	19 May	1.61	13.5	
	20 June$_b$	2.90	24.3	
	Average	1.49 ± 0.35	12.5 ± 2.9	
Puente Hills	8 May	4.29	36.0	38.8
	19 May	3.62	30.4	
	20 June	4.48	37.6	
	Average^b	4.06 ± 1.18	34.0 ± 9.9	

^{a}data from CARB (L. Hunsaker, personal communication, June 2011).

^{b}weighted average, assuming a 50% uncertainty in the individual flux determinations [Taylor, 1997].

3%. In these cases, the flux was averaged and reported in Table 3. Three nearby CH_4 point sources are identified in the 2009 CARB GHG inventory: an oil and gas field power plant, which burns natural gas for fuel; the landfill power plant at Olinda Alpha, which burns landfill gas for fuel; and general stationary combustion from the landfill operations. Inventory data suggest that these three sources together emit between 0.0004 and 0.0015 Gg CH_4/yr, negligible amounts relative to CH_4 emitted directly from the landfill. On 19 May, the NOAA P-3 sampled plumes from the nearby oil and gas power plant and the landfill's power plant, both of which burn natural gas as fuel (Figure 3c). A large spike in CO_2, some CH_4, and perhaps a small amount of CO were encountered in the landfill power plant plume. However, downwind of the landfill in the large plume of CH_4, the CO_2 enhancement does not stand out significantly above the background variability. Therefore, our analysis of P-3 data supports the conclusion from the inventory that landfill CH_4 emissions dominate the observed plume enhancements downwind of Olinda Alpha landfill. Using NOAA P-3 CH_4 data from all five transects, we directly calculate a weighted average CH_4 emission flux via equation (1) of $(1.49 \pm 0.35) \times 10^{25}$ molecules/s, equal to 12.5 ± 2.9 Gg CH_4/yr assuming a constant emission, where the weights are the 50% uncertainty of each determination. For comparison, the CARB GHG inventory emission estimate from the Olinda Alpha landfill is 11.0 Gg/yr for 2008, showing agreement within the errors of the direct estimate using P-3 airborne data.

[27] The second landfill results we examine in depth are from the Puente Hills landfill (34.020°N, 118.006°W) in City of Industry, Los Angeles County, California. Of all California landfills, Puente Hills is the largest emitter of CH_4 in the 2008 CARB GHG inventory. Nearby sources of CH_4 in the 2008 CARB GHG inventory include the Puente Hills power plant (0.00045 Gg CH_4/yr) and the Savage Hills Canyon landfill (1.1 Gg CH_4/yr), both of which are small relative to the CARB GHG inventory of 39 Gg CH_4/yr emission rate for Puente Hills. The NOAA P-3 conducted three daytime boundary layer plume transects from which we determine an average emission flux of $(4.06 \pm 1.18) \times 10^{25}$ molecules/s, which extrapolates to 34.0 ± 9.9 Gg CH_4/yr assuming a constant emission (Table 3). Similar to the findings for Olinda Alpha, the CARB GHG inventory of 39 Gg CH_4/yr for the Puente Hills landfill is in agreement within the errors of the direct estimate using P-3 airborne data.

[28] Quantitative agreement between CH_4 flux estimates from the NOAA P-3 and the 2008 CARB GHG inventory for these two examples supports the use of that inventory to quantify total CH_4 emissions from landfills in the South Coast Air Basin. According to the 2008 CARB GHG inventory, CH_4 emissions from landfills totaled 117 Gg CH_4/yr in the L.A. County portion of the SoCAB, 30% higher than the 90 Gg CH_4/yr for the same geographic area using the CARB GHG inventory in 2008 reported by Hsu et al. [2010], which we attribute to different versions of the CARB GHG inventory.

[29] The 2008 CARB GHG inventory further predicts an emission from landfills of 164 Gg CH_4/yr for the entire SoCAB. On the basis of the agreement with the CARB inventory described above for the emission rates from the two landfills quantified directly by the CalNex P-3 data (50 Gg CH_4/yr, or 30% of the inventory total for the SoCAB), we assume the remaining CARB landfill CH_4 emission estimates are accurate.

4.3. Methane Emissions From L.A. Basin Dairies

[30] Salas et al. [2008] published dairy locations in California for the year 2005, with an estimate of dairy cow population for each. The locations are plotted as filled yellow circles in Figure 1c, and sized by the expected CH_4 emission from enteric fermentation according to the 2009 CARB GHG inventory (144 kg CH_4 per cow per year). According to Salas et al. [2008], all dairies in San Bernardino and Riverside counties were also located in the SoCAB, and 87% of the dairy cows in the SoCAB in 2005 were located in the Chino area (the large grouping of dairies in Figure 1c). The Chino-area dairy operations, which at one time were distributed across the Riverside-San Bernardino county line in satellite images, now appear to be located mainly in San Bernardino County as the Riverside dairies have been converted to residential neighborhoods (e.g., see Google Earth historical imagery since 2000). This declining number of dairies is confirmed by the United States Department of Agriculture (USDA) (http://www.nass.usda.gov/Statistics_by_State/California/Publications/County_Estimates/201005lvscef.pdf), which reports a decrease in dairy cows in San Bernardino and Riverside Counties from 200,000 head in 2005 to 137,500 head in 2010. In addition to dairy cows, dairies also stock immature heifers. Further, there are beef operations in the SoCAB, but these are negligible compared to the San Bernardino and Riverside dairy populations. According to the USDA, there were a total of 431,000 cattle in San Bernardino and Riverside counties in 2005, and 295,000 cattle in 2010. For both years, dairy cows represented approximately 46.5% of the cattle population in the SoCAB. From these dairy and cattle populations, we construct a bottom-up emissions inventory for the SoCAB using the same emission factors as the CARB GHG inventory.

[31] We begin with CH_4 emissions from enteric fermentation. We assign to each of the 137,500 dairy cows in the SoCAB an emission factor of 144 kg CH_4/yr. We assume the remaining 157,500 head are dairy replacements, and assign each an emission factor of 57.7 kg CH_4/yr, or the average emission factor for 0–1 and 1–2 year old dairy replacements in the CARB GHG inventory. We calculate a total of 28.9 Gg CH_4/yr emitted solely from enteric fermentation in the SoCAB.

[32] In addition to enteric fermentation, manure management practices have a substantial effect on CH_4 emissions from livestock operations. In the L.A. basin, dairies typically practice solid storage (http://www.aqmd.gov/rules/doc/r1127/pr1127_task1rpt_20020101.pdf and http://www.arb.ca.gov/planning/sip/sjv_report/addtl_resources.pdf), which emits relatively low levels of CH_4 (17 kg/yr per cow) according to the 2009 CARB GHG inventory. The tradeoff for this practice is that it emits larger amounts of NH_3 than other types of manure management (http://www.epa.gov/ttn/chief/ap42/ch09/draft/draftanimalfeed.pdf). Therefore, if we attribute dry manure management emissions to the SoCAB dairy cow population, and the dry lot emission rate of 2.1 kg CH_4/yr for the remaining heifers, we get an additional 2.7 Gg CH_4/yr from dairy operation manure

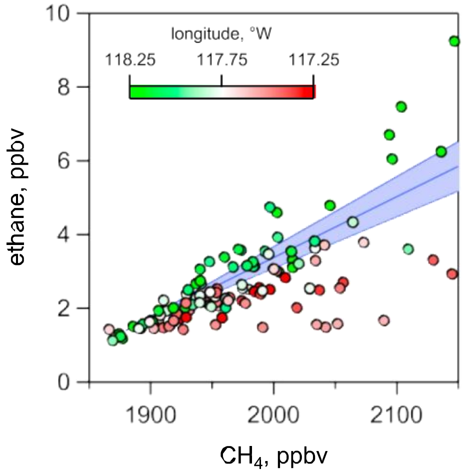

Figure 4. Scatter plot of ethane versus CH$_4$ from the NOAA P-3 data in the L.A. basin. Data points are colored by longitude to show the different distributions of ethane to CH$_4$ in the eastern (red) and western (green) parts of the basin. The blue line represents the slope of 1.65 ± 0.25 % used by Wennberg et al. [2012] to represent the estimated ethane/CH$_4$ ratio of pipeline-quality dry natural gas from the Southern California Gas Company's pipelines.

management in the SoCAB. This results in a total of 31.6 Gg CH$_4$/yr from enteric fermentation and manure management for the SoCAB dairy operations. This is the emission from agriculture and forestry that we add back into the population-apportioned CARB CH$_4$ inventory above (Table 2).

[33] Our estimate of 31.6 Gg CH$_4$/yr, based on inventory data, is less than half of the 76 Gg CH$_4$/yr estimated by Wennberg et al. [2012]. We attribute this difference in bottom-up inventories to the different assumptions of manure management practices. Wennberg et al. [2012] scaled total California CH$_4$ emissions by livestock population, which also assumes the manure management practices from the San Joaquin Valley apply to the L.A. basin. For example, the anaerobic lagoons more commonly used in the San Joaquin Valley emit 325 kg CH$_4$ per cow per year according to the 2009 CARB GHG inventory, significantly higher than 17 kg CH$_4$ per cow per year from dry manure management practices typical of the L.A. basin.

[34] Nowak et al. [2012] used P-3 data from CalNex to derive emissions of ammonia (NH$_3$) from dairy farms in the Chino area. From NOAA P-3 measurements, we determine a CH$_4$ flux from the Chino-area dairies for the same three downwind transects analyzed by Nowak et al. [2012]. Using the Chino to SoCAB population apportionment by Salas et al. [2008], we expect these same Chino-area dairies to emit approximately 28 Gg CH$_4$/yr. CH$_4$ fluxes determined from equation (1) range from 24 ± 12 to 88 ± 44 Gg CH$_4$/yr, and the average of the three transects is 49 ± 25 Gg CH$_4$/yr. This value derived from airborne flux determination lies between the 28 Gg CH$_4$/yr calculated from the inventory assuming dry manure management practices described above, and the estimate by Wennberg et al. [2012] of 76 Gg CH$_4$/yr (less livestock emissions from the SoCAB that are not in the Chino area) assuming mainly wet management practices. We attribute the differences to actual practices in the region, which are likely a mixture of the two manure management approaches. Satellite images of the area show what appear to be several anaerobic lagoons near Chino, California. Our flux determination is therefore consistent with our bottom-up CH$_4$ emission inventory, with room for a mixture of manure management practices, including some anaerobic lagoons, in the L.A. basin.

4.4. Spatial Distribution of Methane Sources

[35] Townsend-Small et al. [2012] concluded that the CH$_4$ emissions in the L.A. region had a stable isotope ratio similar to that of fossil-fuel CH$_4$. This conclusion was based on measurements made at the Mount Wilson Observatory. A back-trajectory [White et al., 2006; http://www.esrl.noaa.gov/psd/programs/2010/calnex/traj/] from MWO for 5 August 2009, the specific day that Townsend-Small et al. [2012] used to determine the excess CH$_4$ stable isotopic ratio, shows the prevailing winds to MWO were from the southwest, or from downtown L.A. and the coast west of downtown L.A. The trajectory tool also shows winds from the eastern basin on the previous day, which was excluded by Townsend-Small et al. [2012] due to lower correlation between the excess CH$_4$ and d^{13}C. We conclude that the MWO data interpreted by Townsend-Small et al. [2012] were dominated by emissions from the western basin only and were not influenced by emissions from either the largest landfills (Puente Hills and Olinda Alpha), or from the dairies in the eastern part of the L.A. basin. This spatially biased sampling is consistent with their conclusion that landfills do not contribute significantly to the total atmospheric CH$_4$ burden in L.A.

[36] Evidence for the heterogeneous spatial distribution of CH$_4$ sources in the SoCAB can be seen in the NOAA P-3 data. Figure 4 shows that the correlation of ethane with CH$_4$ is dependent on the sample location in the L.A. basin. Also, shown in Figure 4 is the slope used by Wennberg et al. [2012] to represent the ethane/CH$_4$ ratio (16.5 ± 2.5 ppt ethane/ppb CH$_4$) in pipeline-quality dry natural gas from the Southern California Gas Company (SoCalGas), the major provider of natural gas to the SoCAB, for 2010. The chemical data in Figure 4 reflect the known source types shown on the map in Figure 1c: the large CH$_4$ sources in the eastern L.A. basin, primarily landfills and dairies, are not significant sources of ethane relative to CH$_4$.

[37] We can reconcile the conclusions of Townsend-Small et al. [2012] and Wennberg et al. [2012] with the CARB GHG inventory by noting that fossil fuel CH$_4$ emissions predominate in the western basin and that landfill and livestock CH$_4$ emissions predominate in the eastern basin. However, in contrast to the findings of Wennberg et al. [2012], we find that natural gas leaks from the SoCalGas and in-home pipelines are not the only possible source of fossil fuel CH$_4$ to the western basin, as described below.

4.5. Light Alkane Emissions From Local Natural Gas Production

[38] Los Angeles was one of only three out of 28 cities characterized by propane and ethane levels within 10% of one another in the atmosphere [Baker et al., 2008], consistent with an enhanced propane source term in L.A. Figure 5 shows correlations of propane versus ethane in whole-air

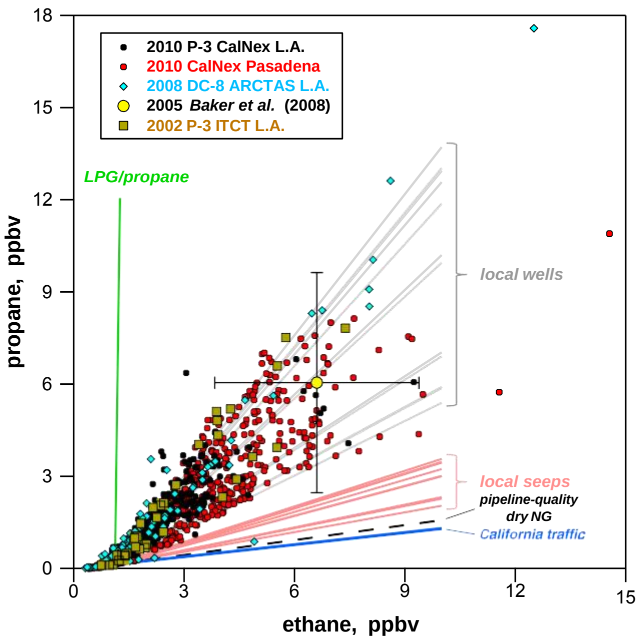

Figure 5. Correlation plot of propane versus ethane from four Los Angeles data sets. Also, plotted are composition ratios of local wells (gray lines) and local seeps (salmon lines) reported by Jeffrey et al. [1991], the composition ratio of pipeline-quality dry natural gas (black dashed line), the propane/ethane emission ratio from a San Francisco Bay-area tunnel study reported by Kirchstetter et al. [1996], and the average composition ratio of liquefied petroleum gas (LPG) or propane (green line).

samples from various aircraft projects in the Los Angeles region (ITCT 2002, ARCTAS 2008, and CalNex 2010), as well as measurements from the CalNex Pasadena ground site in 2010. Also, plotted are lines representing the composition ratios of other possible sources of ethane and propane in Los Angeles.

[39] The L.A. basin is home to oil and gas operations (Figure 1c); the composition ratios depicting possible emissions from local natural gas (gray lines) and local geologic seeps (salmon lines) in Figure 5 are those reported by Jeffrey et al. [1991]. The lower propane content relative to ethane seen in the seeps (e.g., the La Brea tar pits) compared to the local natural gas is attributed to near-surface microorganisms forming shorter chain alkanes from longer chain alkanes during the time the natural gas migrates toward the surface [Jeffrey et al., 1991]. The average propane/ethane ratio for processed gas in SoCalGas pipelines [Wennberg et al., 2012] is plotted as a dashed black line. Pipeline-quality dry natural gas has a low propane/ethane ratio because the natural gas has been processed (i.e., the higher alkanes have been removed from the natural gas) before distribution. The SoCalGas ratio is representative of natural gas piped in from out of state (e.g., from Texas, Wyoming, and Canada); approximately 90% of natural gas used in California is imported (http://www.socalgas.com/regulatory/documents/cgr/2010_CGR.pdf). The on-road emissions are taken from a San Francisco Bay-area tunnel study by Kirchstetter et al. [1996], who reported a vehicular emission ratio of 0.13 mol propane/mol ethane roughly similar to those by Fraser et al. [1998] (0.27 mol propane/mol ethane) and by Lough et al. [2005] (0.06–0.18 mol propane/mol ethane). Vehicle engine exhaust typically contains small, decreasing amounts of CH_4, ethane, and propane due to incomplete combustion, as gasoline and diesel fuel do not contain significant amounts of these light alkanes. The on-road emissions, local geologic seeps, and the pipeline-quality dry natural gas from SoCalGas contain three to five times more ethane than propane and therefore cannot alone explain the ambient ratios measured in the L.A. basin. The propane and ethane composition of unprocessed natural gas from local wells, on the other hand, closely matches the SoCAB ambient measurements from three aircraft campaigns, the CalNex ground site measurements, and the Baker et al. study [2008]. Propane and ethane were also typically enhanced at the same time, with the exception of one sample with elevated propane near the Long Beach area (Figure 1e).

[40] The data in Figure 5 suggest that local oil and gas wells contribute significantly to the atmospheric propane burden in the SoCAB. However, Wennberg et al. [2012] invoked a large source of propane from fugitive losses from the liquefied petroleum gas (LPG) industry (i.e., propane tanks), in addition to leaks from the pipeline-quality dry natural gas distribution system in the L.A. basin. This would be consistent with past works that have found significant fugitive losses of propane in other cities, such as Mexico City [Blake and Rowland, 1995]. We therefore extend our analysis to incorporate ethane, propane, and C_4 (n- and i-butane) and C_5 (n- and i-pentane) isomers to better attribute and quantify the sources of light alkanes and CH_4 to the SoCAB atmosphere. Light alkanes are plotted in Figure 6, with lines depicting the composition of natural gas in SoCalGas pipelines [Wennberg et al., 2012] and of on-road emissions [Kirchstetter et al., 1996]. We neglect chemical processing of these long-lived alkanes ($\tau \geq 3$ days at OH = 1×10^6 molecules/cm^3) as we find no detectable difference between daytime and nighttime enhancement ratios relative to CO, similar to the findings of Borbon et al. [2013] for n-butane and CO at the CalNex Pasadena ground site. Atmospheric enhancement ratios of propane, n-butane, and i-butane (Figures 6b–6d) relative to ethane are consistent with emissions having the composition of local natural gas [Jeffrey et al., 1991]. On-road emissions do not appear to contribute significantly to the CH_4, ethane, and propane in the L.A. atmosphere, and pipeline-quality dry natural gas and/or local geologic seeps do not appear to contribute significantly to the propane and n-butane relative to ethane in the L.A. atmosphere. Based on these observations, we conclude that the local natural gas industry contributes a significant fraction to the total atmospheric C_2–C_4 alkane abundances, including propane, in the L.A. basin. We infer CH_4 emissions from the local natural gas industry are non-negligible as well, as discussed below.

4.6. Source Attribution

[41] Here we quantify total emissions of C_2–C_5 alkanes in the L.A. basin by multiplying their observed enhancement ratios to CO by the CARB SoCAB emission inventory for CO. Figure 7 shows C_2–C_5 alkanes plotted versus CO with their respective ODR fits. The slopes from these fits are used in equation (2) along with the projected 2010 CARB CO

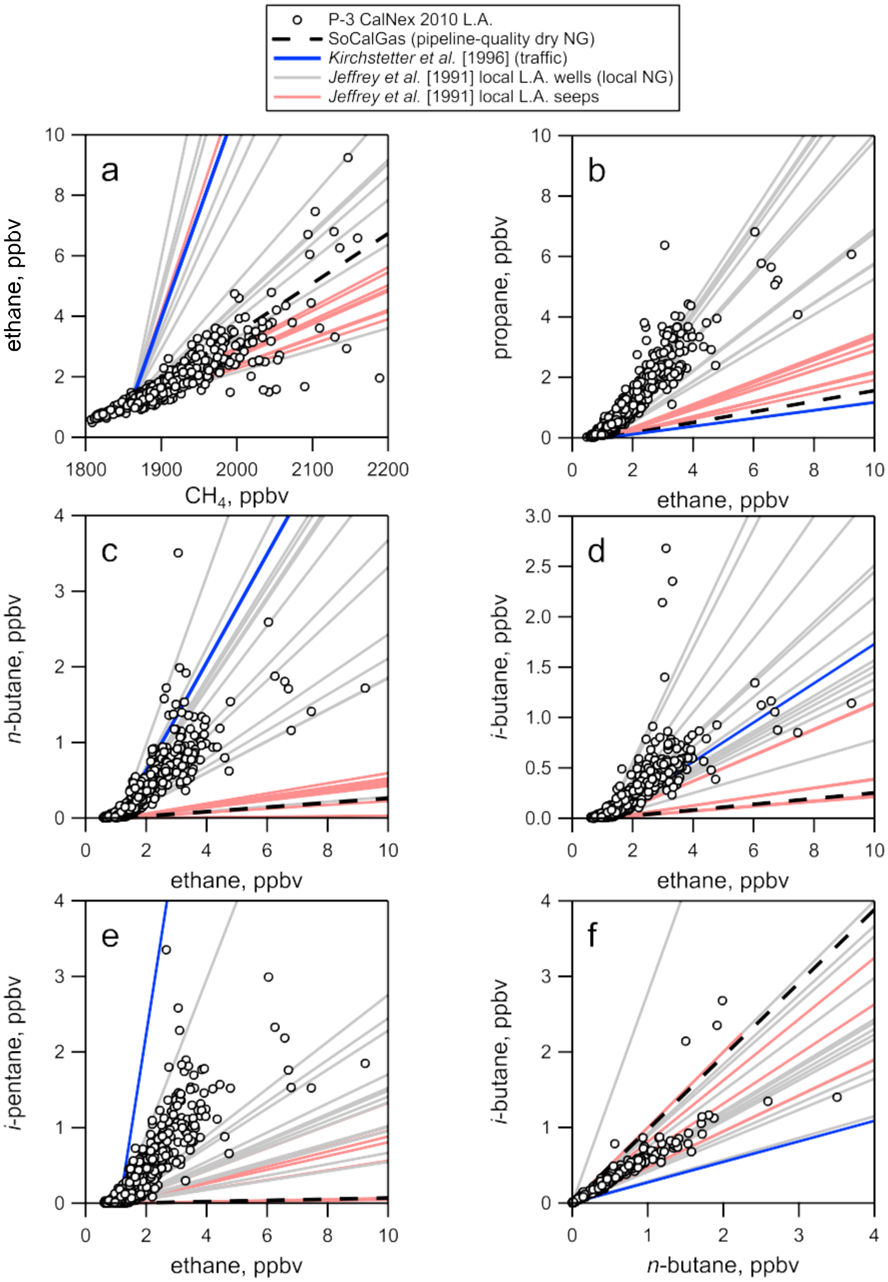

Figure 6. Plots of CH_4 and C_2–C_5 alkanes from the NOAA P-3 CalNex data set, selected for the SoCAB (black circles). Nighttime and high-altitude data are included. Also, included for reference are the emission ratios of mobile sources from Kirchstetter et al. [1996] (blue line), composition ratios measured by Jeffrey et al. [1991] for local natural gas (gray lines) and local geologic seeps (salmon lines), and composition ratios from pipeline-quality dry natural gas (NG) delivered by SoCalGas (dashed black line). These ratios were plotted from daytime background levels.

inventory to calculate annual alkane emissions in the SoCAB. We assume the slopes represent a direct emission with no chemical aging. These emissions are listed in the rightmost column of Table 4. Also, listed in Table 4 are the estimated contributions from mobile sources in the SoCAB, using C_1–C_5 to CO emission ratios from Kirchstetter et al. [1996] (modified as discussed below) and CO emissions from the mobile sources category in the projected 2010 CARB CO inventory, equal to 925 Gg CO/yr, in equation (2).

[42] Wennberg et al. [2012] attributed the inventory CH_4 shortfall [Wunch et al., 2009; Hsu et al., 2010] by ascribing much of the CH_4 and ethane enhancements to fugitive losses of processed pipeline-quality dry natural gas. They further suggest the majority of atmospheric propane is due to LPG industry/propane tank fugitive losses. Here, we consider other possible explanations of the sources of CH_4 and light alkanes in the L.A. basin for the following two reasons. First, the source attribution by Wennberg et al. [2012] leaves little room for CH_4 emissions from landfills, wastewater

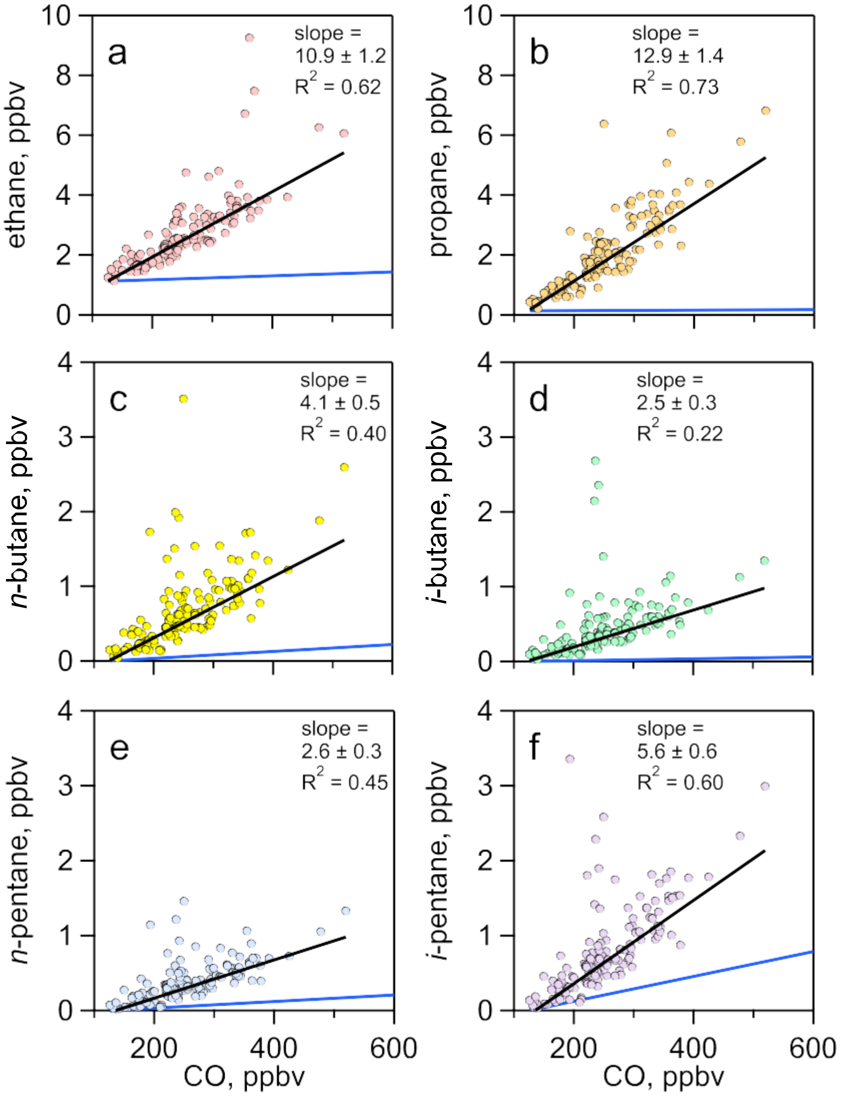

Figure 7. (a–f) Daytime measurements of alkanes versus CO from the NOAA P-3 in the L.A. basin during CalNex are plotted as filled circles. For comparison, the alkane/CO emission ratios from a San Francisco Bay-area tunnel study [Kirchstetter et al., 1996] are plotted as a solid blue line, which extends to the right axis. The slope from a weighted ODR (given as ppt alkane/ppb CO), total slope uncertainty, and R^2 are given in each panel.

treatment plants, and dairies in the L.A. basin. This solution seems unlikely based on direct emissions flux estimates using the P-3 data downwind of landfills and dairies in the SoCAB, as described above. Second, the attribution by Wennberg et al. [2012] would leave a shortfall in both n- and i-butane emissions that cannot be explained by gasoline evaporation or emissions from mobile sources. We use a multivariate approach based on a linear combination of the CH_4 and light alkane compositions from known sources in order to attribute and quantify total CH_4 and C_2–C_5 alkane emissions in the South Coast Air Basin.

[43] We include seven different source types (sectors) with distinct and known CH_4 and C_2–C_5 alkane compositions (Figure 8) in the following analysis: (1) Leaks of processed dry natural gas from pipelines, and/or emissions from local geologic seeps (this approach cannot distinguish between pipeline-quality dry natural gas and local seeps); (2) CH_4-dominated emissions, such as from landfills, wastewater treatment plants, and dairies; (3) Leaks of unprocessed, local natural gas; (4) Leaks of liquefied petroleum gas from propane tanks; (5) On-road combustion emissions from mobile sources; (6) Emissions of CH_4 and C_2–C_5 alkanes in the SoCAB from other source sectors; and (7) Evaporative emissions from gasoline. These are described briefly below.

[44] 1. The South Coast Air Basin contains 14.8 million people, and SoCalGas delivers approximately 11 Tg/yr of natural gas to the Los Angeles area. Additionally, the Earth's natural degassing is a known source of CH_4, ethane, and propane to the atmosphere [Etiope et al., 2008; Etiope and Ciccioli, 2009], and the L.A. basin contains abundant geologic hydrocarbon reserves [Jeffrey et al., 1991]. We group fugitive losses from processed pipeline-quality dry natural gas with the emissions from local geologic seeps because the C_1–C_4 emissions from these sources are not sufficiently different to be treated separately in our linear

Table 4. Derived Emissions in the South Coast Air Basin (In Gg/yr) for 2010 From Each Source Sector Used in Linear Analysis

	Pipeline-Quality Dry NG/Local Seeps	CH_4-Dominant (Landfills, Dairies, Etc.)	Local NG	LPG/Propane	Evaporated Gasoline	Mobile Sources	CARB Other	Summed Source Totals	Estimated SoCAB Total[a]
CH_4	192 ± 54	182 ± 54	32 ± 7	-	-	4.9 ± 1.3	1.2 ± 0.3	411 ± 77	411[b] ± 37
Ethane	5.9 ± 1.7	-	4.5 ± 1.0	0.05 ± 0.02	0.0 ± 0.0	0.6 ± 0.1	0.3 ± 0.1	11.4 ± 1.9	11.4[b] ± 1.6
Propane	1.5 ± 0.4	-	9.9 ± 2.0	6.6 ± 2.9	0.006 ± 0.001	0.1 ± 0.0	1.6 ± 0.4	19.8 ± 3.6	19.8 ± 2.7
n-Butane	0.3 ± 0.1	-	5.9 ± 1.2	0.02 ± 0.01	0.5 ± 0.1	0.3 ± 0.1	1.4 ± 0.4	8.5 ± 1.3	8.3 ± 1.2
i-Butane	0.3 ± 0.1	-	2.2 ± 0.5	0.13 ± 0.06	0.08 ± 0.02	0.04 ± 0.01	1.8 ± 0.5	4.6 ± 0.6	5.1 ± 0.7
n-Pentane	0.07 ± 0.02	-	2.2 ± 0.5	-	2.6 ± 0.4	1.0 ± 0.1	0.3 ± 0.1	6.6 ± 0.6	6.5 ± 0.9
i-Pentane	0.11 ± 0.03	-	2.4 ± 0.5	0.003 ± 0.001	7.6 ± 1.0	3.9 ± 0.5	0.03 ± 0.01	14.1 ± 1.2	14.1 ± 1.8

[a] includes measurement, ODR fit, and inventory uncertainty.

[b] Wennberg et al. [2012] estimate emissions to the SoCAB of 440 ± 100 Gg CH_4/yr and 12.9 ± 0.9 Gg ethane/yr.

combination analysis (illustrated by the similarity in slopes of the dashed black and salmon-colored lines in Figure 6). Both pipeline-quality dry natural gas and local seep emissions contain similar amounts of CH_4 and ethane relative to one another and have less C_3–C_5 alkanes relative to ethane than local, unprocessed natural gas. For pipeline-quality dry natural gas, most C_{3+} alkanes are removed during the processing stage, which is typically done close to the source, which for ~90% of the natural gas used in California is in Canada, Wyoming, and/or Texas. For local seeps, most C_{3+} alkanes are either preferentially adsorbed in shallow sediments compared to CH_4 or biodegraded by microbes in the Earth's crust during the seepage of local natural gas to the surface [Jeffrey et al., 1991]. We use SoCalGas samples of pipeline-quality natural gas from 2010 [Wennberg et al., 2012] to represent this source and estimate the uncertainty of the composition at 15%.

[45] 2. CH_4-dominant emission sources, which for this analysis include landfills, wastewater treatment plants, and livestock, emit CH_4 but no significant amounts of C_2–C_5 alkanes. This is represented in our analysis as a unit vector containing only CH_4.

[46] 3. From 2007 to 2009, the oil and gas industry in the L.A. basin produced roughly 12–13 billion cubic feet of natural gas per year, mostly associated gas from oil wells (http://www.conservation.ca.gov/dog/pubs_stats/annual_reports/Pages/annual_reports.aspx). We use an average of the samples reported by Jeffrey et al. [1991] weighted by 2009 gross natural gas production per field and estimate the uncertainty of this composition at 25%.

[47] 4. Two types of LPG are sold in the Los Angeles area: One is almost completely composed of propane; the other has traces of n- and i-butane (http://www.arb.ca.gov/research/apr/past/98-338_1.pdf). We use the ratios reported by Blake and Rowland [1995] from direct analysis of LPG in Los Angeles, which is consistent with an average of the two types of LPG sold in L.A., and estimate the uncertainty of the composition at 10%.

[48] 5. On-road combustion emissions are modified from the work of Kirchstetter et al. [1996] by multiplying emission ratios of alkanes to CO by the 925 Gg CO/yr from on-road sources in the projected 2010 CARB CO inventory. The C_4–C_5 emissions represent unburned fuel and are typically proportional to the fuel composition; the C_1–C_3 emissions typically represent incomplete combustion products. To account for differing fuel compositions since the time of the Kirchstetter et al. [1996] study, the i- and n-butane emissions calculated for mobile sources in the SoCAB (Table 4) have been scaled to the i-pentane emissions based on their relative abundance in gasoline [Gentner et al., 2012].

[49] 6. There are additional sources of light alkanes in the SoCAB. We use the 2010 CARB speciated inventory for total organic gases (http://arb.ca.gov/ei/speciate/interopt10.htm) and projected 2010 total organic gas emissions (http://www.arb.ca.gov/app/emsinv/fcemssumcat2009.php) for the SoCAB to estimate emissions of light alkanes not specified in other source sectors. These include emissions from aerosol spray cans and other consumer products, coatings and solvents, adhesives and sealants, and fiberglass and plastics manufacturing. For example, propane, n-, and i-butane are commonly used as propellants in aerosol spray cans, having replaced CFCs in the United States in the 1970s (e.g., CARB estimates 0.6 Gg of aerosol antiperspirant vapors were emitted to the SoCAB in 2010, of which 0.14 Gg, 0.03 Gg, and 0.15 Gg were propane, n-, and i-butane, respectively). These emissions are summed and listed in the "CARB Other" column in Table 4. Emissions from natural gas leaks, petroleum refining, petroleum marketing (gas stations), landfills and composting, and mobile sources are not included in these totals, because they are accounted for elsewhere in other source sectors. We estimate a 25% uncertainty in the "CARB Other" inventory.

[50] 7. Emissions ratios from evaporated gasoline were calculated from 10 gasoline samples from five Pasadena gas stations in the summer of 2010, weighted by estimated sales of 80% regular and 20% premium [Gentner et al., 2012]. Uncertainties are those reported by Gentner et al. [2012].

[51] First, we start with estimated annual C_1–C_5 emissions in the SoCAB (rightmost column of Table 4), then subtract modified on-road emissions [Kirchstetter et al., 1996] and projected emissions of C_1–C_5 alkanes from other sources (source sector 6, above). Next, we place the remaining source sector characteristics into a matrix and solve for the fraction each source contributes to the remaining alkane observations for the L.A. basin based on each source's relative abundances of various light alkanes. The matrix has five columns representing the five remaining source sectors, and seven rows containing C_1–C_5 alkanes. We solve the following equation [e.g., see section 4.2 of Kim et al., 2011]

$$A_{i;j}x_j = b_i \qquad (3)$$

where $A_{i,j}$ is a matrix of the C_1–C_5 alkane composition, i, for the source sectors, j, defined above; x_j is the fraction each source contributes to the total observed emissions; and b_i

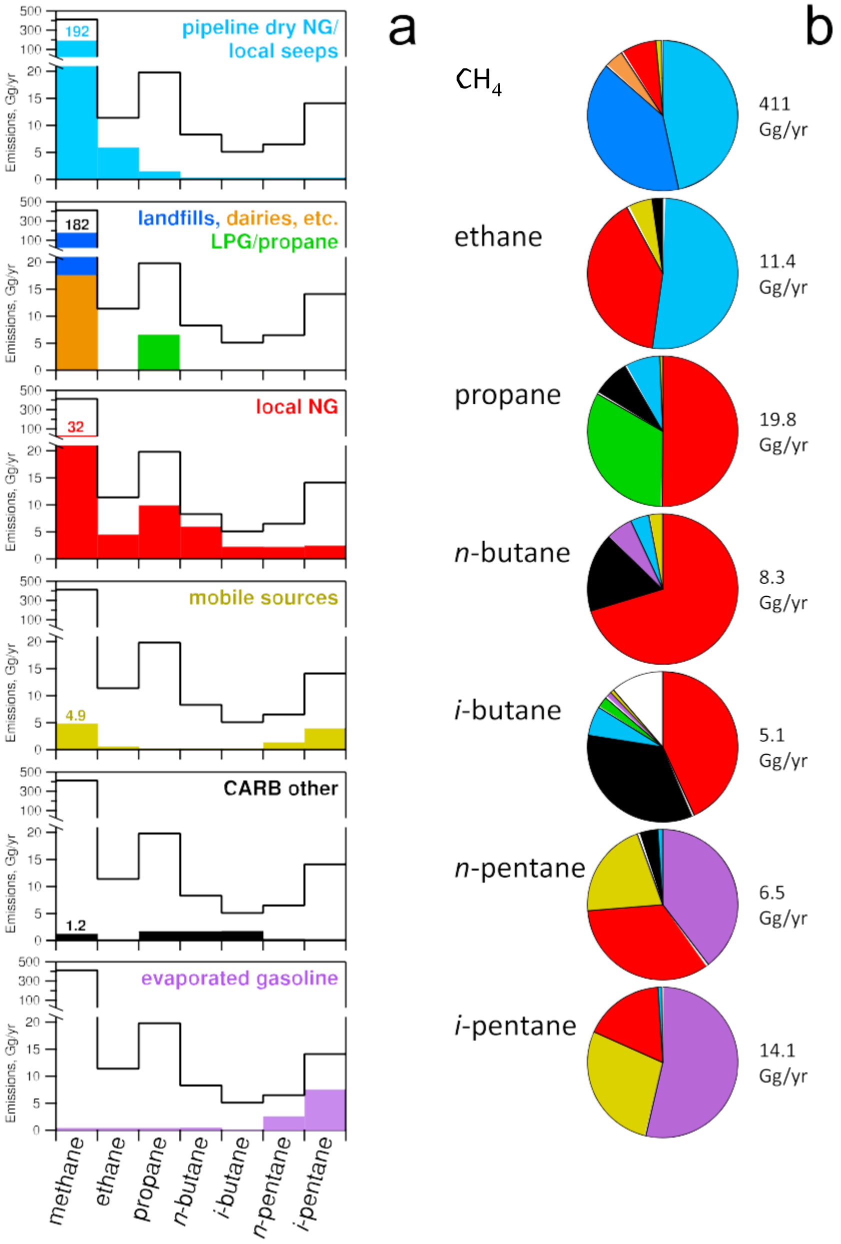

Figure 8. (a) Results from a linear least squares solution to a combination of six sources and seven trace gas species in the SoCAB. The thick black line represents the estimated total annual emission to the SoCAB for seven hydrocarbons (CH_4 and C_2–C_5). The colored bars represent the fraction of the total contributed by each of the six source sectors used in the linear analysis. CH_4 emissions are written above the bar. (b) Pie charts for the same data in Figure 8a showing the relative contributions from each source for each of seven alkanes, colored as in Figure 8a. The white region in the i-butane pie chart represents the 11% shortfall between our source attribution and our estimated emission to the SoCAB, though it is within the uncertainties of these two values. The total emission of the alkane to the SoCAB is given to the right of each pie chart.

is the total observed emission of alkane i minus the contributions from the mobile and "other" source sectors (Table 4). The columns of the matrix A are proportional to the first five columns of Table 4. We solve for the linear least squares solution that minimizes $(Ax - b)$. Uncertainties in the derived x_j are estimated by a sensitivity study, where we run the solution 1,000,000 times by randomly varying $A_{i,j}$ and b_i according to their estimated uncertainties, then use the standard deviation of the 1,000,000 x_j determinations to estimate the uncertainty in the source attribution fraction. The source attribution fractions and their uncertainties are multiplied by the total estimated SoCAB emission for each alkane and then are summed with the uncertainties added in quadrature. CH_4 and C_2–C_5 alkane emissions totals, their uncertainties, and the contributions from each source type are given in Table 4. The source attribution solution solves the observed SoCAB alkane emission to within each alkane's emission uncertainty.

[52] Our modeled source attribution differs from the alkane source distribution in the L.A. basin as set forth by Wennberg et al. [2012]. From a total calculated source of 410 ± 40 Gg CH_4/yr in the SoCAB, we determine that 47% comes from leaks of processed pipeline-quality dry natural gas and/or from local geologic seeps; 44% of the CH_4 comes from the sum of landfill, wastewater treatment, and dairy emissions; 8% from the leaks of unprocessed natural gas from production in the western L.A. basin; and 1% from mobile sources. The attribution is presented graphically in Figure 8. Figure 8a displays the total SoCAB emissions as a black horizontal line in each panel, with contributions from the different source sectors given below the line by the filled bars. Figure 8b shows the proportion that each source sector contributes to the derived total emissions of each alkane.

[53] Our analysis attributes CH_4 emissions of 192 ± 54 Gg CH_4/yr to leaks of pipeline-quality dry processed natural gas and/or leaks from local geologic seeps but does not distinguish further between these two different sources. This value is nearly a factor of 5 greater than the population-apportioned 2009 CARB GHG emissions inventory estimate of 40 Gg CH_4/yr lost from natural gas pipelines in the SoCAB. Our estimate of 192 Gg CH_4/yr is less than the maximum emission of 400 ± 150 Gg CH_4/yr estimated by Wennberg et al. [2012]. Our estimate would represent approximately 2% of the natural gas delivered to customers in the SoCAB and, including storage and deliveries to customers outside the SoCAB, 1% of the gas flowing into the basin [Wennberg et al., 2012]. These percentages would decrease linearly with any CH_4 emissions attributed to local geologic seeps. Farrell et al. [2013] estimate up to 55 Gg CH_4/yr are emitted from the La Brea Tar Pits in western L.A. County alone; if accurate, this would imply pipeline leaks of only 0.7% of the gas flowing into the basin, or a factor of at least two lower than the 2% proposed by Wennberg et al. [2012].

[54] Our analysis attributes 182 ± 54 Gg CH_4/yr in the SoCAB to emissions from landfills, wastewater treatment, and dairies. SoCAB landfills account for 164 Gg CH_4/yr in the 2008 CARB GHG inventory; a value supported by our analysis in section 4.2. In section 4.3, we estimated in a bottom-up inventory that SoCAB dairies emitted 31.6 Gg CH_4/yr. Wennberg et al. [2012] estimated an emission of 20 Gg CH_4/yr from wastewater treatment. These independent estimates sum to 216 Gg CH_4/yr and are consistent with our source apportionment using NOAA P-3 data.

[55] CH_4 emissions of 31.9 ± 6.5 Gg CH_4/yr are ascribed to leaks of local, unprocessed natural gas and would represent 17% of the local production in 2009, the latest year for which data are available (http://www.conservation.ca.gov/dog/pubs_stats/annual_reports/Pages/annual_reports.aspx). This number assumes a CH_4 composition of 72.5% by volume for natural gas produced in the South Coast Air Basin, which is calculated as an average from the samples reported by Jeffrey et al. [1991] weighted by 2009 production. Our derived value of 17%, although a surprisingly high amount of local production, is consistent with a nascent bottom-up estimate under way at CARB. A new bottom-up inventory survey, conducted by CARB for the calendar year 2007 but not yet incorporated into the official GHG inventory, indicates that 109 Gg CH_4/yr, since revised to 95.5 Gg CH_4/yr (S. Detwiler, personal communication, October 2012), were emitted throughout California by the oil and gas industry via combustion, venting, and fugitive losses (Table 3-1, http://www.arb.ca.gov/cc/oil-gas/finalreport.pdf). This updated value is a factor of 2.5 larger than the current CARB GHG inventory tabulation of 38 Gg CH_4/yr from oil and gas extraction for 2007 in California. CH_4-specific emissions for the South Coast Air Quality Management District in the new CARB survey report show 24.6 Gg CH_4/yr were emitted in the SoCAB (S. Detwiler, personal communication, October 2012). According to the survey, emissions in the SoCAB accounted for 26% of the revised statewide total oil and gas operations CH_4 emission in 2007, despite accounting for only 4.4% of statewide natural gas production in the basin that year (http://www.conservation.ca.gov/dog/pubs_stats/annual_reports/Pages/annual_reports.aspx). Thus, the survey responses suggest a CH_4 leak rate of 12% of local production in the L.A. basin. Thus, our estimate of CH_4 emissions from local natural gas for 2010 based on P-3 data from CalNex is within a factor of 1.5 of the CARB bottom-up inventory currently in development based on the 2007 survey. According to the survey, other oil and gas-producing regions in California show smaller CH_4 loss rates than that from the SoCAB. For instance, statewide losses of CH_4 represent approximately 2.1% of statewide production, and CH_4 losses from the San Joaquin Air Quality District represent approximately 1.4% of production (from Oil and Gas Districts four and five). This indicates that losses from natural gas production are proportionally larger in the L.A. basin than elsewhere in the State of California.

[56] A propane emission of 6.6 ± 2.9 Gg/yr from LPG/propane tanks would represent approximately 1% of sales (http://www.aqmd.gov/ceqa/documents/2012/aqmd/finalEA/PAR1177/1177_FEA.pdf), which is less than the ~4% calculated by Wennberg et al. [2012], and closer to the 0.6% estimated from the document cited.

[57] Finally, our analysis suggests a resolution to the discrepancies noted above between previous top-down assessments and the bottom-up inventory calculations for CH_4 in the SoCAB [e.g., Wunch et al., 2009; Hsu et al., 2010; Townsend-Small et al., 2012; Wennberg et al., 2012]. We conclude the most probable source for the excess atmospheric CH_4 is likely due to a combination of primarily leaks, not accurately represented in the current CARB GHG inventory, from natural gas pipelines and urban distribution systems and/or from local geologic seeps, and secondarily leaks of unprocessed natural gas from local oil and gas production centered in the western L.A. basin. This finding is based on the characteristic enhancement ratios of CH_4 and the various C_2–C_5 alkanes consistently observed in the L.A. atmosphere, and is further supported by the spatial information provided by P-3 samples during CalNex. Finally, the updated values for local oil and gas industry emissions in the recent GHG survey commissioned by CARB, when incorporated fully into the official CARB GHG record, will likely help to reduce this long-standing discrepancy between top-down assessments and bottom-up inventories.

5. Conclusions

[58] We use aircraft measurements of CH_4, CO, and CO_2 during the CalNex field campaign to show that emissions of CH_4 to the L.A. basin are greater than can be explained by official state bottom-up inventories apportioned by population, consistent with published work. The ratio of the CARB CO and CO_2 inventories is in better agreement with our measurements of CO/CO_2 in the Los Angeles atmosphere than was the case for the analysis by Wunch et al. [2009], which we attribute either to improved CARB inventories, the present use of a basin-wide data set to determine basin-wide emission ratios, or both.

[59] From crosswind plume transects downwind of the two largest landfills in the basin, we determine CH_4 fluxes that are consistent with the 2008 CARB GHG inventory values, which total 164 Gg CH_4/yr emitted from all landfills in the South Coast Air Basin. CH_4 emission fluxes were also determined for Chino-area dairies in the eastern L.A. basin. Flux estimates from these dairies ranged from 24 ± 12 to 87 ± 44 Gg CH_4/yr, and the average flux is consistent with a revised bottom-up inventory originally compiled by Salas et al. [2008] and with previous inventory estimates [Wennberg et al., 2012].

[60] Finally, we present a top-down assessment of C_2–C_5 alkane sources in the L.A. basin, and then apportion CH_4 and the C_2–C_5 alkanes to specific source sectors in the region. Using this source apportionment approach, we estimate that 32 ± 7 Gg of CH_4/yr, or 8% of the total CH_4 enhancement observed in the SoCAB during CalNex, came from the local oil and gas industry. This number represents approximately 17% of the natural gas produced in the region, within a factor of 1.5 of that calculated from a recent survey that will be used to update the CARB bottom-up inventory. We estimate 182 ± 54 Gg CH_4/yr are emitted by landfills, dairies, and wastewater treatment, which is consistent with bottom-up inventories, and 192 ± 54 Gg CH_4/yr are emitted of processed pipeline-quality dry natural gas and/or from geologic seeps in the region. We further conclude that leaks of processed pipeline-quality dry natural gas and/or local geologic seeps, and unprocessed natural gas from local oil and gas production are the most likely major contributors to the previously noted discrepancy between CH_4 observations and State of California inventory values for the South Coast Air Basin. Our findings suggest that basin-wide mobile studies targeting CH_4 and C_2–C_5 alkane emissions from natural gas pipelines and urban distribution systems, geologic seeps, and local oil and gas industry production sites would be useful to further distinguish the sources of CH_4 in the L.A. basin.

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References

Baker, A. K., A. J. Beyersdorf, L. A. Doezema, A. Katzenstein, S. Meinardi, I. J. Simpson, D. R. Blake, and F. S. Rowland (2008), Measurements of nonmethane hydrocarbons in 28 United States cities, Atmos. Environ., 42, 170–182, doi:10.1016/j.atmosenv.2007.09.007.

Blake, D. R., and F. S. Rowland (1995), Urban leakage of liquefied petroleum gas and its impact on Mexico City air quality, Science, 269, 953–956.

Boggs, P. T., et al. (1989), Algorithm 676 – ODRPACK: Software for weighted orthogonal distance regression, ACM Trans. Math. Software, 15, 348–364.

Borbon, A., et al. (2013), Emission ratios of anthropogenic VOC in northern mid-latitude megacities: Observations vs. emission inventories in Los Angeles and Paris, J. Geophys. Res. Atmos., 118, 2041–2057, doi:10.1002/jgrd.50059.

Brioude, J., et al. (2012), Top-down estimate of surface flux in the Los Angeles Basin using a mesoscale inverse modeling technique: Assessing anthropogenic emissions of CO, NO_x, and CO_2 and their impacts, Atmos. Chem. Phys. Discuss., 12, 31439–31481, doi:10.5194/acpd-12-31439-2012.

Colman, J. J., A. L. Swanson, S. Meinardi, B. C. Sive, D. R. Blake, and F. S. Rowland (2001), Description of the analysis of a wide range of volatile organic compounds in whole air samples collected during PEM-tropics A and B, Anal. Chem., 73(15), 3723–3731, doi:10.1021/ac010027g.

Conway, T. J., et al. (2011), Atmospheric carbon dioxide dry air mole fractions from the NOAA ESRL carbon cycle cooperative global air sampling network, 1968–2010, Version: 2011-10-14, Path: ftp://ftp.cmdl.noaa.gov/ccg/co2/flask/event/.

Dlugokencky, E. J., et al. (2011), Atmospheric methane dry air mole fractions from the NOAA ESRL carbon cycle cooperative global air sampling network, 1983–2010, Version: 2011-10-14, Path: ftp://ftp.cmdl.noaa.gov/ccg/ch4/flask/event/.

Etiope, G., and P. Ciccioli (2009), Earth's degassing: A missing ethane and propane source, Science, 323, doi:10.1126/science.1165904.

Etiope, G., K. R. Lassey, R. W. Klusman, and E. Boschi (2008), Reappraisal of the fossil methane budget and related emission from geologic sources, Geophys. Res. Lett., 35, L09307, doi:10.1029/2008GL033623.

Farrell, P., D. Culling, and I. Leifer (2013), Transcontinental methane measurements: Part 1. A mobile surface platform for source investigations, Atmos. Environ., doi:10.1016/j.atmosenv.2013.02.014.

Fraser, M. P., G. R. Cass, and B. R. T. Simoneit (1998), Gas-phase and particle-phase organic compounds emitted from motor vehicle traffic in a Los Angeles roadway tunnel, Environ. Sci. Technol., 32, 2051–2060.

Gentner, D. R., et al. (2012), Elucidating secondary organic aerosol from diesel and gasoline vehicles through detailed characterization of organic carbon emissions, Proc. Natl. Acad. Sci. U. S. A., 109(45), 18318–18323, doi:10.1073/pnas.1212272109.

Gilman, J. B., et al. (2010), Surface ozone variability and halogen oxidation throughout the Arctic and sub-Arctic springtime, Atmos. Chem. Phys., 10, 10,223–10,236, doi:10.5194/acp-10-10223-2010.

Gurney, K. R., D. L. Mendoza, Y. Zhou, M. L. Fischer, C. C. Miller, S. Geethakumar, and S. de la Rue du Can (2009), High resolution fossil fuel combustion CO_2 emissions fluxes for the United States, Environ. Sci. Technol., 43, 5535–5541, doi:10.1021/es900806c.

Holloway, J. S., R. O. Jakoubek, D. D. Parrish, C. Gerbig, A. Volz-Thomas, S. Schmitgen, A. Fried, B. Wert, B. Henry, and J. R. Drummond (2000), Airborne intercomparison of vacuum ultraviolet fluorescence and tunable diode laser absorption measurements of tropospheric carbon monoxide, J. Geophys. Res., 105(D19), 24,251–24,261, doi:10.1029/2000JD900237.

Hsu, Y.-K., T. VanCuren, S. Park, C. Jakober, J. Herner, M. FitzGibbon, D. R. Blake, and D. D. Parrish (2010), Methane emissions inventory verification in southern California, Atmos. Environ., 44, 1–7, doi:10.1016/j.atmosenv.2009.10.002.

Jeffrey, A. W. A., et al. (1991), Geochemistry of Los Angeles Basin Oil and Gas Systems, in Active Margin Basins, Memoir 52, edited by K. T. Biddle, pp. 197–219, Amer. Assoc. Petr. Geologists, Tulsa, Okla.

Kim, S.-W., et al. (2011), Evaluations of NO_X and highly reactive VOC emission inventories in Texas and their implications for ozone plume simulations during the Texas Air Quality Study 2006, Atmos. Chem. Phys., 11, 11361–11386, doi:10.5194/acp-11-11361-2011.

Kirchstetter, T. W., B. C. Singer, R. A. Harley, G. R. Kendall, and W. Chan (1996), Impact of oxygenated gasoline use on California light-duty vehicle emissions, Environ. Sci. Technol., 30, 661–670.

Kort, E. A., P. K. Patra, K. Ishijima, B. C. Daube, R. Jiménez, J. Elkins, D. Hurst, F. L. Moore, C. Sweeney, and S. C. Wofsy (2011), Tropospheric distribution and variability of N_2O: Evidence for strong tropical emissions, Geophys. Res. Lett., 38, L15806, doi:10.1029/2011GL047612.

Lough, G. C., J. J. Schauer, W. A. Lonneman, and M. K. Allen, (2005), Summer and winter nonmethane hydrocarbon emissions from on-road motor vehicles in the midwestern United States, J. Air Waste Manage. Assoc., 55, 629–646.

Neuman, J. A., et al. (2012), Observations of ozone transport from the free troposphere to the Los Angeles basin, J. Geophys. Res., 117, D00V09, doi:10.1029/2011JD016919.

Novelli, P. C., and K. A. Masarie (2010), Atmospheric carbon monoxide dry air mole fractions from the NOAA ESRL carbon cycle cooperative global air sampling network, 1988–2009, Version: 2011-10-14, Path: ftp://ftp.cmdl.noaa.gov/ccg/co/flask/event/.

Nowak, J. B., J. A. Neuman, R. Bahreini, A. M. Middlebrook, J. S. Holloway, S. A. McKeen, D. D. Parrish, T. B. Ryerson, and M. Trainer (2012), Ammonia sources in the California South Coast Air Basin and their impact on ammonium nitrate formation, Geophys. Res. Lett., 39, L07804, doi:10.1029/2012GL051197.

Peischl, J., et al. (2012), Airborne observations of methane emissions from rice cultivation in the Sacramento Valley of California, J. Geophys. Res., 117, D00V25, doi:10.1029/2012JD017994.

Ryerson, T. B., et al. (1998), Emissions lifetimes and ozone formation in power plant plumes, J. Geophys. Res., 103(D17), 22,569–22,583.

Ryerson, T. B., et al. (2013), The 2010 California Research at the Nexus of Air Quality and Climate Change (CalNex) field study, J. Geophys. Res. Atmos., doi:10.1002/jgrd.50331.

Salas, W. A., et al. (2008), Developing and applying process-based models for estimating greenhouse gas and air emission from California dairies, California Energy Commission, PIER Energy-Related Environmental Research, CEC-500-2008-093, http://www.energy.ca.gov/2008publications/CEC-500-2008-093/CEC-500-2008-093.PDF.

Schauffler, S. M., E. L. Atlas, D. R. Blake, F. Flocke, R. A. Lueb, J. M. Lee-Taylor, V. Stroud, and W. Travnicek (1999), Distributions of brominated organic compounds in the troposphere and lower stratosphere, J. Geophys. Res., 104(D17), 21,513–21,535, doi:10.1029/1999JD900197.

Simpson, I. J., et al. (2010), Characterization of trace gases measured over Alberta oil sands mining operations: 75 speciated C_2–C_{10} volatile organic compounds (VOCs), CO_2, CO, CH_4, NO, NO_y, O_3 and SO_2, Atmos. Chem. Phys., 10, 11,931–11,954, doi:10.5194/acp-10-11931-2010.

Taylor, J. R. (1997), An Introduction to Error Analysis, The Study of Uncertainties in Physical Measurements, 2nd Edition, p. 174, University Science Books, Sausalito, Calif.

Townsend-Small, A., S. C. Tyler, D. E. Pataki, X. Xu, and L. E. Christensen (2012), Isotopic measurements of atmospheric methane in Los Angeles, California, USA: Influence of “fugitive” fossil fuel emissions, J. Geophys. Res., 117, D07308, doi:10.1029/2011JD016826.

Trainer, M., B. A. Ridley, M. P. Buhr, G. Kok, J. Walega, G. Hübler, D. D. Parrish, and F. C. Fehsenfeld (1995), Regional ozone and urban plumes in the southeastern United States: Birmingham, a case study, J. Geophys. Res., 100(D9), 18,823–18,834.

Washenfelder, R. A., et al. (2011), The glyoxal budget and its contribution to organic aerosol for Los Angeles, California, during CalNex 2010, J. Geophys. Res., 116, D00V02, doi:10.1029/2011JD016314.

Wennberg, P. O., et al. (2012), On the sources of methane to the Los Angeles atmosphere, Environ. Sci. Technol., 46(17), 9282–9289, doi:10.1021/es301138y.

White, W. H., J. A. Anderson, D. L. Blumenthal, R. B. Husar, N. V. Gillani, J. D. Husar, and W. E. Wilson Jr. (1976), Formation and transport of secondary air pollutants: Ozone and aerosols in the St. Louis urban plume, Science, 194, 187–189, doi:10.1126/science.959846.

White, A. B., C. J. Senff, A. N. Keane, L. S. Darby, I. V. Djalalova, D. C. Ruffieux, D. E. White, B. J. Williams, and A. H. Goldstein (2006), A wind profiler trajectory tool for air quality transport applications, J. Geophys. Res., 111, D23S23, doi:10.1029/2006JD007475.

Wunch, D., P. O. Wennberg, G. C. Toon, G. Keppel-Aleks, and Y. G. Yavin (2009), Emissions of greenhouse gases from a North American megacity, Geophys. Res. Lett., 36, L15810, doi:10.1029/2009GL039825.

Appendix F

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Report to

Damascus Citizens for Sustainability
25 Main Street
Narrowsburg, New York 12764

Report on a Survey of Ground-Level Ambient Methane Levels in the Vicinity of Wyalusing, Bradford County, Pennsylvania

November 2013

by

Bryce F. Payne Jr.[1] and Robert Ackley[2]

[This report is subject to revision.]

NOTE: Figures follow text.

There have been numerous reports of methane emissions related to shale gas development in the vicinity of Wyalusing, Bradford County, Pennsylvania. In the interest of furthering the understanding of those fugitive methane events Damascus Citizens for Sustainability engaged Gas Safety, Inc. to survey ambient air methane levels in the vicinity of Wyalusing, PA. The survey covered parts of 9 townships on both sides of the Susquehanna River (Figure 1 –

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following text) from Towanda on the northwest to Wyalusing on the central eastern side. Survey coverage was restricted to readily identifiable public roadways. Consequently, the survey was most intense from the Susquehanna River west to Pennsylvania Route 187.

Though the survey results do not prove a relationship between ambient air methane contamination and groundwater contamination, it is clearly suggestive. Further, it also suggests shale gas well operations in that area still did not have control of the gas that has been developed there. In fact, as will be discussed, survey data indicates there may be gas control problems in about 10% of the survey area resulting in elevated methane levels in most of the area.

In addition, detection of any level of methane above normal background for an area indicates only two possible conditions: diffuse, non-point emissions are occurring over some portion of the area, or, one or more point sources are active within the area.

Conditions during the Survey

The survey effort involved two separate survey field work efforts, one on 31 January and the other 3-4 June 2013. Weather conditions at the time of the January survey were not ideal. Winds were from the west at speeds consistently near 20 miles per hour (29 feet per second). Under these conditions methane emissions from any source disperse rapidly. Consequently, elevated methane levels due to such emissions are more difficult to detect than under more favorable wind conditions. Functionally this means that, during a road survey, detection of elevated methane levels requires the sources be larger or more intense and in closer proximity to the survey vehicle path than under more favorable wind conditions. However, such wind conditions do cause methane emissions to be swept along the ground surface farther and faster. Consequently, methane emissions appear as a general elevation of methane levels over a wider area, instead of localized markedly elevated peaks.

During the 3-4 June field work weather conditions were more favorable. The wind was from the north-northwest at an average speed of 5 miles per hour (around 8 feet per second). Under these conditions methane emissions would be expected to be detectable as low concentration plumes extending for an appreciable distance to the south-southeast of the source. Mixing layer structure and height was not estimated during the survey, but conditions should have favored typical lower atmospheric mixing patterns in which most methane emissions diffuse rapidly upward.

Results of the January Survey

As anticipated due to the wind conditions the methane levels were moderately elevated widely over the survey area. Typical methane level observed during the survey was low. The average methane level was 1.86 ppm, with a minimum of 1.79 ppm, 90% were below 1.91 ppm, and 99% below 2.08 ppm.[3] Under such high wind conditions, the layer of the atmosphere that normally forms next to the land surface[4] is swept away by air that would normally move at altitudes of a few hundred to a few thousand feet above. Under gentler wind conditions gases released into the air tend to accumulate in plumes as they dissipate into the turbulent but lower-wind-speed layer of air next to the land surface. Under sustained high wind conditions the air from the higher layer sweeps down and across the land surface rapidly sweeping any released gases across the land surface and up into the atmosphere.

Figure 2 shows an oblique westward view of the survey area in which the data was processed to remove values lower than 2.2 ppm and vertically exaggerate those over 2.2 ppm by a factor of 1000. In effect, this approach visually defines methane levels above 2.2 ppm as elevated methane levels (EMLs). This graphical rendering shows around 18 locations with elevations above 2.2 ppm. There also appear to be many locations with EMLs near 2.2 ppm. This, however, is an artifact of the low resolution of this image and the high resolution of the survey data set. When this image is examined at higher resolution most of the apparent near-2.2-ppm EMLs disappear.

To allow examination of smaller EMLs another image of data was prepared with the methane data processed to remove values below 1.9 ppm and vertically exaggerate values >1.9 ppm by a factor of 100. The lower 1.9-ppm cutoff and vertical exaggeration preserved EMLs that were not apparent upon high resolution examination of Figure 2, as illustrated by Figures 3 and 4. The >1.9-ppm image is not shown as it is visually nearly flat at the resolution that can be rendered on a single page of this report. In the >1.9-ppm image 57 EMLs were indentified as sufficiently clear to merit further examination (see Appendix B for a listing of those EMLs by location). Of those 57 EMLs, 43 were in proximity to and nearly-downwind of gas pipelines, gas well pads, farms, industrial facilities with apparent waste water treatment ponds or lagoons.

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[3] During survey runs the vehicle has to make stops. The CRDS methane instrument collects data continuously. Consequently, geographically disproportionate amounts of data accumulate whenever the vehicle stops. Geographically disproportionate data accumulations are removed from the data set before statistical analysis. Images are generated using the full raw data sets.

[4] Planetary boundary layer or mixing layer. See Manhattan extended report for more detailed discussion.NEED LINK HERE

Further identification of the methane sources causing the other 14 EMLs was beyond the scope of the survey work.

Despite the strong wind conditions a relatively large methane plume was detected. The plume was detected over an area running from Wysox 2.5 miles southward along the river and up to 3.6 miles to the east. The plume was not present on a later pass through the same area. The extent and consistency of this plume over such a large area under such windy conditions, and its relatively sudden disappearance suggest a sizeable release of methane upwind of the plume area that ended sometime during the survey. Identification of a likely source was beyond the scope of the survey work. It is noteworthy that this plume was again present during the June survey. The plume may have been related to a number of gas wells generally north of Wysox.

Conclusions from 31 January Survey

The strong wind conditions during the methane survey caused rapid mixing and lateral dispersal of methane from any sources in or near the survey area. Under such conditions detection of elevated methane levels is limited to those resulting from larger emissions or those from sources in close proximity to the roadway. The rapid mixing and lateral dispersal causes methane levels in the area to appear more uniformly elevated than would be the case under less windy conditions. This was indicated by the slightly elevated mean (1.86 ppm) and narrow range of methane levels (1.79-1.91 ppm) that accounted for the 90% of the data (further discussed in comparison to the June data follows below). All the other 10% of the data indicating methane levels above 1.91 ppm occurred at less than 60 locations. Among those locations, 43 were in the vicinity of candidate potential methane sources, in most cases gas pipelines or gas well pads. At 14 locations with elevated methane levels candidate potential methane sources were not readily apparent.

Results of the 3-4 June Survey

As expected under the more favorable wind conditions on 3-4 June, methane plumes were detectable over much larger areas than during the extreme wind conditions of the 31 January survey. Elevated methane levels occurred over much of the survey area. Additionally the methane instrument (cavity ring down spectrometer[5]) was run during travel from the survey area and during a brief observational trip to the Leroy Township area. Those two legs of the

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[5] http://www.picarro.com/technology/cavity_ring_down_spectroscopy

survey trip provided methane measurements in geographically and geologically adjacent areas that can be reasonably regarded as comparable areas with limited or no shale gas well activity. That area is referred to as the Reference Area in the remainder of this report. It includes data from valleys, along a river, and two town/city areas. Hence, the Reference Area can be reasonably considered to have all likely natural and human-caused methane sources typical for the geographical/geological area, but with minimal large-scale agricultural, industrial or shale gas sources. Also, of some interest is recognition that the methane survey work included parts of two areas under Pennsylvania Department of Environmental Protection Consent Orders. An image displaying the results of the June survey is provided in Figure 5.

It should be borne in mind that the survey work was limited to publicly accessible roads. The survey, therefore, measures the impacts of methane emissions sources at considerable distances from those sources. Consequently, seemingly minor changes, in the tenths or hundredths of a part per million, in ambient air methane levels are of considerable importance in locating methane emissions sources and assessing their broader area impacts.

The June survey average methane level was 1.83 ppm, with a minimum of 1.75 ppm, 90% were below 1.88 ppm, and 99% below 2.05 ppm.[3] Given the difference in wind conditions, these levels were quite similar to those seen in the January survey. For comparison, in the Reference Area the average methane level was 1.78 ppm, with a minimum of 1.76 ppm, 90% were below 1.79 ppm, and 99% below 1.81 ppm.[3] Since much of the survey area is affected by the same type and frequency of methane sources that occur in the Reference Area, one would expect that much of the survey area data would be similar. This was, in fact, found to be the case. It can be seen in Figure 6 that in the Reference Area 97% of the methane levels were below 1.8 ppm, while in the survey area in June, 37% were, but in the survey area in January less than 1% were below 1.8 ppm. These results suggest that methane emissions in about 37% of the survey area are effectively similar to the Reference Area. The strong winds during the January compared to the June survey were probably the cause of the apparent reduction in total area with readings below 1.8 ppm (37% of the area in June compared to <1% in January), Emissions that on 3-4 June were rising into the air more normally, whereas on 31 January emissions were being rapidly mixed and swept over the land surface by the strong winds.

Looking at another methane value of interest, the maximum methane level measured in the Reference Area was 1.88 ppm. In the survey area on 3-4 June 10% of the measurements exceeded the Reference Area maximum, and on 31 January 16%. Consequently, it is reasonable to conclude that at least 10% of the survey area is impacted by methane sources that do not occur in the Reference Area. As previously mentioned, these are agricultural and industrial sources. Field observations and examination of satellite imagery allowed determination that some of the methane sources causing the elevated methane were agricultural or industrial, other than shale gas development. The plumes of the ag/industrial sources appeared less extensive than the plumes of the sources associated with shale gas development. Most of the shale gas methane emissions sources appeared likely to be well pads and pipelines.

With regard to the relationship between ambient air methane surveys and locations of methane sources potentially impacting an area, it is interesting to consider the survey covered parts of the areas under two PaDEP Consent Orders. Those two Orders were between the PaDEP and Chesapeake Appalachia, LLC, dated 16 May 2011[6]. The two Orders were designated for impact areas referred to by PaDEP as Paradise Road and Sugar Run. It should be borne in mind that at the time of the survey, the Consent Order impact areas were not specifically known to GSI and were not specifically targeted. The general outline of the survey area was selected by DCS based on reports in the media and from residents. The specific area was determined by the operational conditions GSI encountered in the field. Consequently, the survey covered the Consent Orders impact areas only coincidentally. Still the survey did include about 2/3 of the Paradise Road and ½ of the Sugar Run Consent Order impact areas. It can be readily observed in Figure 5 that elevated methane levels were concentrated within the Paradise Road impact area compared to the remainder of the survey. There were elevated methane levels in other parts of the survey area but the concentration in the central part of the Paradise Road impact area is distinct. Though this does not prove a relationship between ambient air methane contamination and groundwater contamination, it is clearly suggestive. Further, it also suggests shale gas well operations in that area still did not have control of the gas that has been developed there. In fact, as already mentioned, the survey data indicates there may be gas control problems in about 10% of the survey area resulting in elevated methane levels over 60-90% of the area.

In addition, detection of any level of methane above normal background for an area indicates only two possible conditions: diffuse, non-point emissions are occurring over some portion of the area, or, one or more point sources are active within the area. Non-point sources are difficult to assess, precisely because they are diffuse. As mentioned previously, at the end of the survey work reported here a cursory evaluation run was made to the area of a previously documented shale gas well impact in Leroy Township. NEED LINK HERE That site is of interest in this discussion because on the land surface methane emissions occur as a non-point source, with gas emerging from many points over a area of uncertain extent. During the earlier evaluation of that site

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[6] This PA DEP Consent Order available HERE: https://www.dropbox.com/s/3r34e3ggb88qxbo/161%20Consent%20Agreem%20Susquehana%20River.pdf

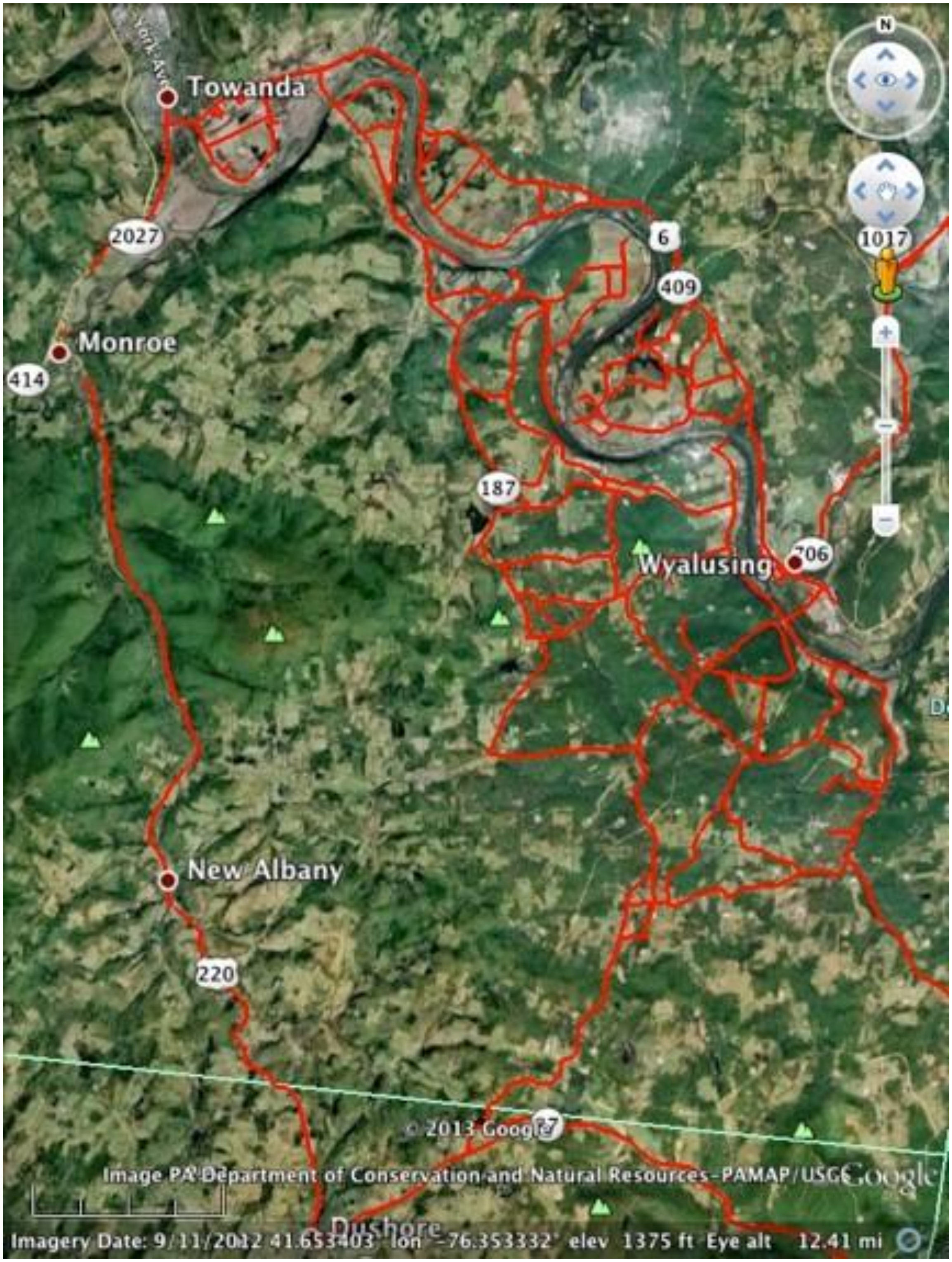
nearly pure natural gas was encountered within inches of the soil surface, but on the nearest road, about 100 yards away, and downwind at the time, only a few ppm of methane were detected. Despite gas well remediation measures, the 4 June run along the same roads confirmed methane levels remain in the range of a few ppm, suggesting the methane migration problem still exists. A cursory water sample test also indicated water in the area still has very high methane levels. Methane contamination was prevalent in the area during the prior evaluation. The Leroy Township situation is troubling with regard to health and safety, and discouraging with regard to the capability of industry to effectively correct gas well problems when they occur.

Point sources of methane present a slightly different set of concerns. A substantial amount of methane is necessary to raise methane levels even slightly over an extensive area, as measured from our survey over public roads. If that amount of methane is being emitted at one or a few point sources, then the concentration of methane in the vicinity of those sources will likely be hazardous with respect to explosion or asphyxiation. Consequently, the methane levels measured during the survey indicate there likely are point sources associated with some shale gas wells in the area that do give rise to hazardous conditions. Those point sources need not necessarily be at the gas well itself, as the gas may find underground pathways to emerge in water wells, homes or other structures, as occurred in Leroy Township, and the Paradise Road and Sugar Run impact areas.

Conclusions

Methane from any source rapidly diffuses and rises in the air. Consequently, detection of possible methane sources from any distance away requires extremely sensitive measurement capabilities. The GSI survey approach takes advantage of extremely sensitive measurement instrumentation to detect small increases in ambient air methane levels as an indication of probable methane emissions sources in a given area. Based on the data collected using that equipment, we conclude that the Towanda-Wyalusing area is probably substantially impacted by methane emissions from shale gas wells both within and beyond the survey area, depending on wind conditions. The coincidence of two DEP methane migration impact areas, Paradise Road and Sugar Road, and the most marked ambient air methane levels suggests there are still gas control problems associated with the shale gas wells there, as well as in another documented impact area in Leroy Township also cursorily measured following the main survey. A rapid water test in the Leroy area confirmed the water in that area is still contaminated with methane. These survey results suggest methane contamination continues and measures taken by gas well operators with regard to methane migration problems that have occurred in these three areas have likely been only partially effective.

Figure 1. Overhead image of roads traveled during the survey of ambient air methane levels in the vicinity of Wyalusing, PA on 31 January 2013 (Google Earth).



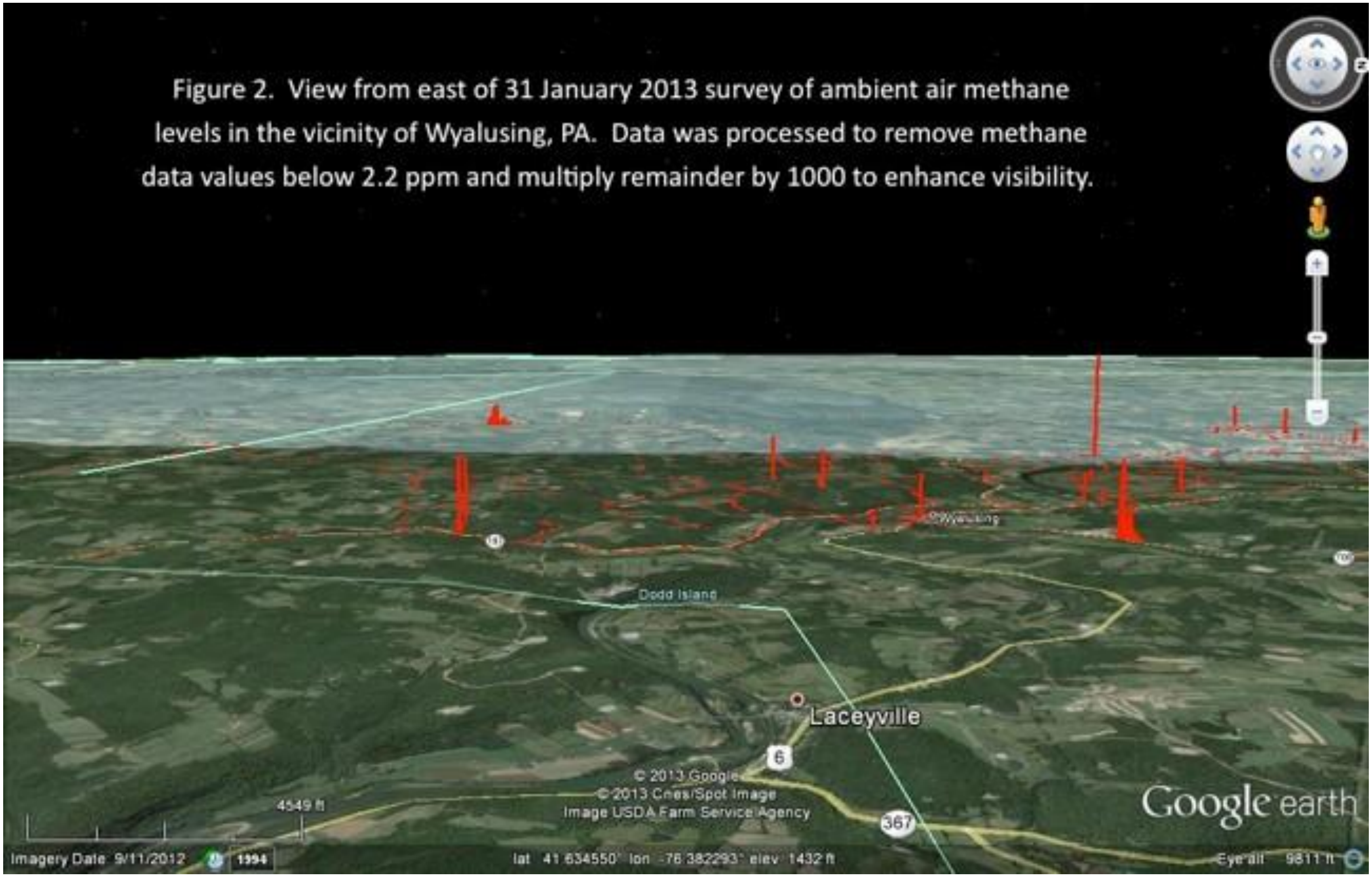


Figure 2. View from east of 31 January 2013 survey of ambient air methane levels in the vicinity of Wyalusing, PA. Data was processed to remove methane data values below 2.2 ppm and multiply remainder by 1000 to enhance visibility.

Figure 3. An elevated methane level as rendered by processing of the Wyalusing 31 January 2013 methane survey data to remove values <2.2ppm and multiply remainder by 1000. Compare to same elevated methane location in Figure 4.

Figure 4. An elevated methane level as rendered by processing of the Wyalusing 31 January 2013 methane survey data to remove values <1.9ppm and multiply remainder by 100. Compare to same elevated methane location in Figure 3.

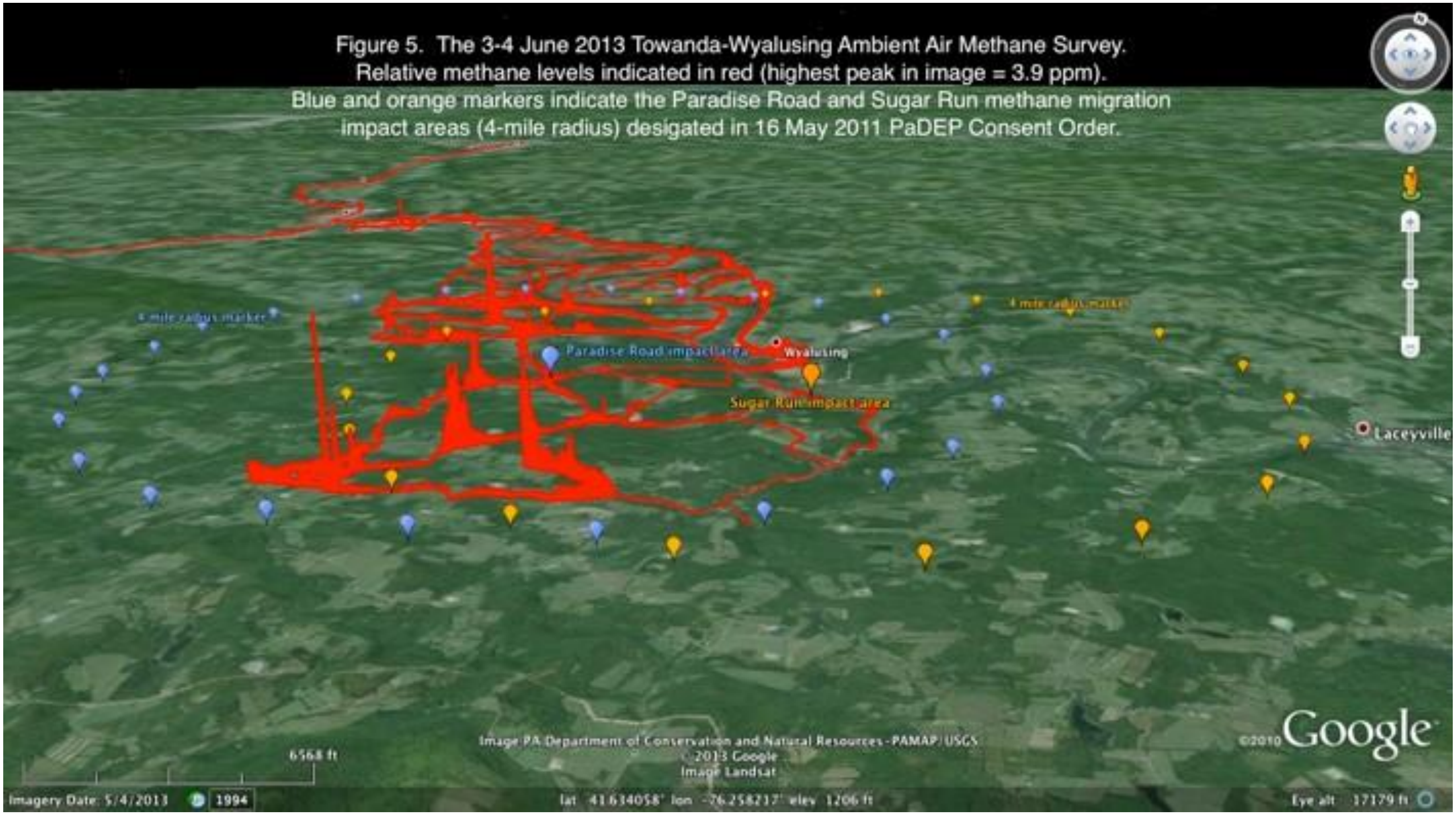
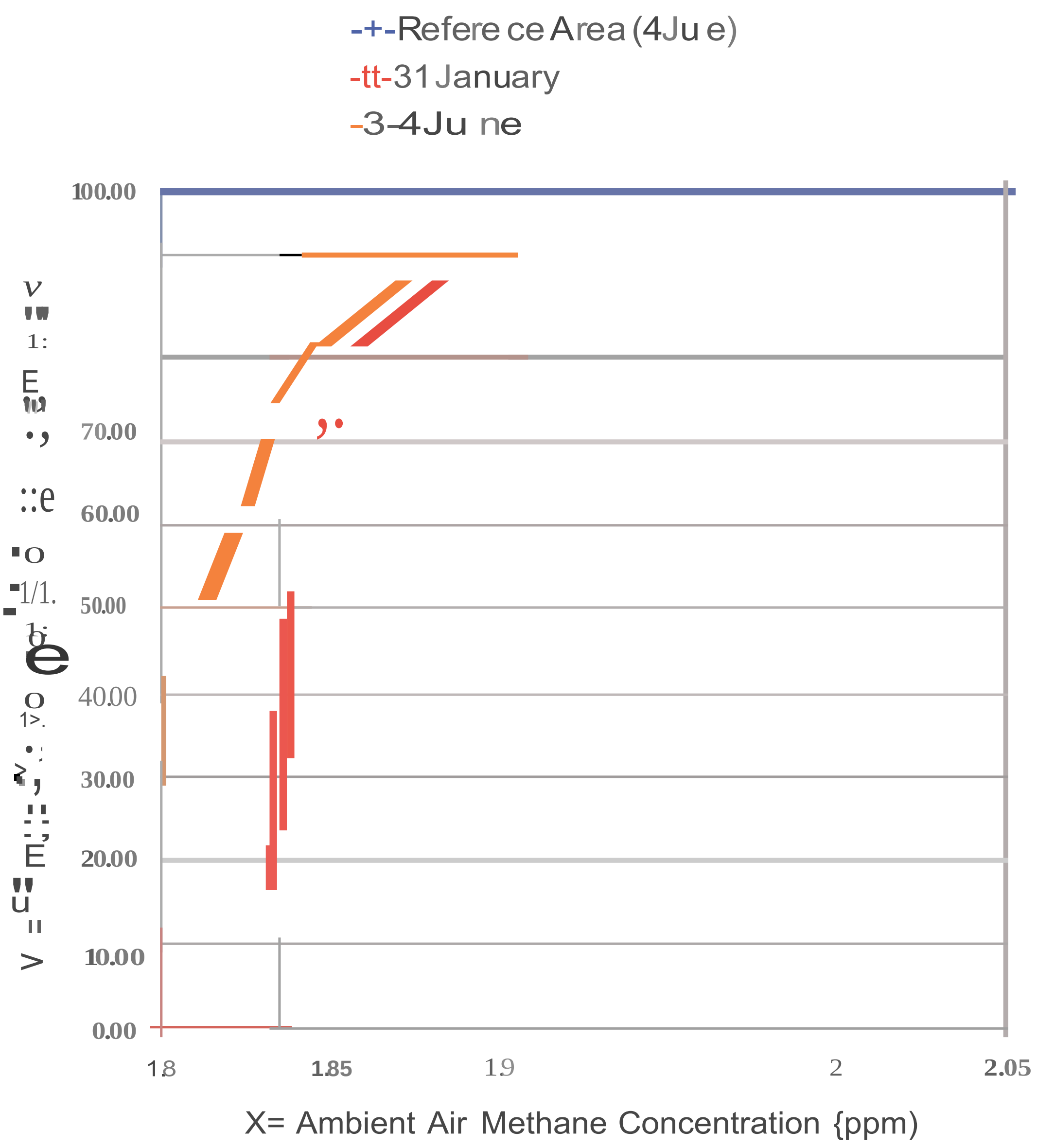


Figure 5. The 3-4 June 2013 Towanda-Wyalusing Ambient Air Methane Survey.
Relative methane levels indicated in red (highest peak in image = 3.9 ppm).
Blue and orange markers indicate the Paradise Road and Sugar Run methane migration impact areas (4-mile radius) desigated in 16 May 2011 PaDEP Consent Order.

Figure 6. Ambient Air Methane Surveys Towanda-Wyalusing Area, PA January and June 2013



Appendix G

Gas Safety Incorporated
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Report to the Clean Air Council
on
8 June 2012 Field Inspection and Methane Sampling Survey
of
Parts of Leroy, Granville and Franklin Townships
Bradford County, Pennsylvania

NOTE: Specific location identification information is avoided in this report pending approval of involved or potentially involved parties.

SUMMARY

A portable laser-based methane measurement system was used to survey methane levels in northeastern Leroy Township, Bradford County, Pennsylvania and adjacent parts of Granville and Franklin Townships on 8 June 2012. The methane system reports methane levels in air to the nearest part per billion (ppb) every 3-4 seconds. During the survey over 7,600 methane measurements were made. The survey data indicated one or more substantial methane emissions were occurring in an area near and to the west of H Rockwell Road and Route 414 giving rise to a ground level plume that expanded to cover at least 4.2 square kilometers over a period of 3.5 hours. The size and rate of expansion of the plume suggested large amounts of methane were being emitted to the atmosphere. Heavily methane contaminated residential water wells occurred in and around the same area, and documentation indicated heavy contamination has existed for at least several months. Bubbling gas in Towanda Creek suggest fugitive gas from shale gas wells may be travelling through faults and fractures, which also carry local ground water, hence, impact local water wells. Collectively the data and observations suggest natural gas has pervaded an extensive subsurface area beyond the area where elevated ground-level methane was found during this survey effort. If that is correct, then more surface emissions are likely and should be expected. The issues and concerns presented in this report require more thorough investigation for confirmation and quantification.

BACKGROUND

A number of dramatic fugitive methane emissions were reported to have begun in Leroy Township on 19 May 2012. Reports suggested a substantive loss of control of natural gas flows from one or more of the shale gas wells in the Township may have occurred. In the interest of verifying and developing independent documentation of the reportedly large increases in natural gas emissions, the Clean Air Council ("CAC", Philadelphia, PA) contracted Gas Safety, Inc. ("GSI", Southboro, MA) to do a one-day sampling and area visit to ascertain the locations of observed or suspected natural gas emissions. The intention was for GSI to use a customized, portable Cavity Ring-Down Spectrometry (CRDS) methane measurement instrument to investigate and document the occurrence (or not) of the reported emissions.

A major concern was to perform the assessment as soon as possible to better ascertain the possible initial intensity and extent of the event; that is, this would preferably be a short notice, rapid response effort. Other concerns were GSI instrument availability and efficient use of field time with the instrument. In order to assure a one-day effort would be as productive as practical, GSI and CAC contacted various parties in pursuit of information regarding specific locations of reported point-source gas emissions. Like the survey trip itself, such requests for information had to be short notice, rapid response efforts. In the interest of openness and sharing of information GSI proposed to provide through CAC its findings to cooperating parties. GSI contacted the Emergency Management Agency of Bradford County, which preliminarily offered to share its own records regarding the initial reports of the sudden onset gas emissions event. CAC and GSI also contacted various private parties with similar data sharing offers and rapid response requests for information and property access. Within 24 hours of such requests, and despite initially positive responses, only 3 private parties agreed to provide information or access to suspected emissions or impacted areas on private property. Ultimately no specific identification of or authorization for access to the actual point locations of ongoing natural gas emissions was obtained in time for the survey. Hence, work was limited to surveying methane levels on public roadways and verifying methane in well water in three residences and collecting anecdotal reports on three others.

Weather conditions were mild and favorable. Barometric pressure was steady. Winds were from the west-northwest increasing steadily throughout the day from nearly calm to a few miles per hour by the end of the survey work.

The group involved in the methane sampling survey (listed just below) met at the junction of Routes 414 and 514 in the northwest corner of Franklin Township at approximately 09:15 AM on 8 June 2012.

Carolyn Knapp, Bradford County resident
Dan Natt, Bradford County resident
Matt Walker, Clean Air Council
Ron Kanter, videographer, Clean Air Council
Dr. Brian Redmond, PG, Wilkes University,
    Dept. of Environmental Engineering and Earth Sciences
Bob Ackley, Gas Safety, Inc.
Dr. Bryce F. Payne Jr., Gas Safety, Inc.

METHANE IN RESIDENTIAL WATER WELLS

A total of four residences (referred to as house1, house2,…) were visited, all served by on-site wells with an interview at house 5 regarding houses 5 and 6. House1 was vacant. It was reported that the residents had vacated due to the inconvenience of and health concerns related to elevated levels of methane and contamination in well water. The house could not be entered, and due to lack of power, no well water could be sampled. Concentrations of methane in the air on the property were normal (normal background ambient air methane 1.75-1.95 ppm).

House2 was located on a farm near a gas well pad (Morse 3H and 5H wells). Most of the area had elevated ambient air methane levels (max. 2.5 ppm) that appeared possibly associated with animal manure accumulations on the farm. However, in areas where there was substantial manure, the presumed likely source of the methane, ambient methane levels were rarely above background and never exceeded 2.2 ppm. Upslope from the farm building area ambient air methane levels were normal. At 200 meters east of the gas well pad methane levels were normal. Down slope, toward Towanda Creek methane levels were elevated, with three locations showing >100 ppm in the ambient air just above the surface of the creek bank. In these instances the methane could have been biogenic or fugitive thermogenic, but sampling conditions did not permit collection of samples for isotope analysis.

The water at the kitchen tap in house3 and house4 was supersaturated with methane. Upon flowing from the faucet the water appeared “milky” due to the large amount of fine methane bubbles present. The fine bubbles coalesced over a period of several seconds causing a pronounced effervescence. High levels of methane in the gas evolved from the tap water were confirmed with the CRDS instrument. No attempt was made to verify initial methane concentration in the tap water, but reports of analyses of samples previously collected by PaDEP or contractors indicated that the well water in these homes had been confirmed to contain methane levels from 50 to 100 milligrams per liter, much greater than saturation under atmospheric pressure (about 28 milligrams per liter). Ongoing supersaturation of well water can only occur if there is substantial water “head” pressure in the well and the methane is under sufficient pressure to reach aquifers under such pressure. It should also be noted that such methane levels are sufficient to pose asphyxiation hazards if used for showering or other high water uses in close quarters, symptoms of which the residents of these properties reported.

An additional inquiry was made at another residence (designated house 5). This was a no-notice contact initially to request information on ownership of the adjacent property. The occupant at house5 reported the well water at that house was similarly heavily contaminated, as well as the well of a close relative who lived in another nearby house (house6).

The wellheads at houses 3-6 had been equipped with passive or wind turbine vents, reportedly by either PaDEP or gas company contractors. Such vents are not designed to prevent or treat contamination of water in wells with conditions and methane exposures of the type that can cause such super-saturation with methane. Presumably the passive vents were installed to prevent pressure driven flow of methane into the homes through possible underground pathways. Though clearly better than the risk of not venting, the application of only passive vents leave the residents under continuing risk of exposures to asphyxiating concentrations of methane, ignore the at least substantial nuisance of having to use methane-super-saturated water, and the potential for serious eruptive releases of methane up through the water well. In addition, such levels of methane contamination necessarily imply the possibility of indirect effects on water quality due to induced biological and chemical changes in the ground water and the mineral medium through which it flows. Such effects might take months or years to become fully apparent, and present a serious concern with regard to long-term degradation of aquifers in areas where even less intensive methane contamination occurs.

In summary, of 6 houses visited or about which information was obtained, 5 had well water that was supersaturated with methane. All 5 of those in which methane contamination was observed or reported lie north of Towanda Creek. Four of the five contaminated residences were occupied at the time of this inquiry, and at all 4, passive vents had been installed with the foreseeable lack of effect on methane contamination of the water. The intensity of the methane contamination seems to require more definitive treatment measures as well as efforts to identify the source or sources of the contamination and actions to prevent long-term degradation of aquifers.

SURVEY OF THE AREA FOR METHANE IN THE AIR

Cavity Ring-Down Spectrometry and Baseline Ground-Level Methane Data

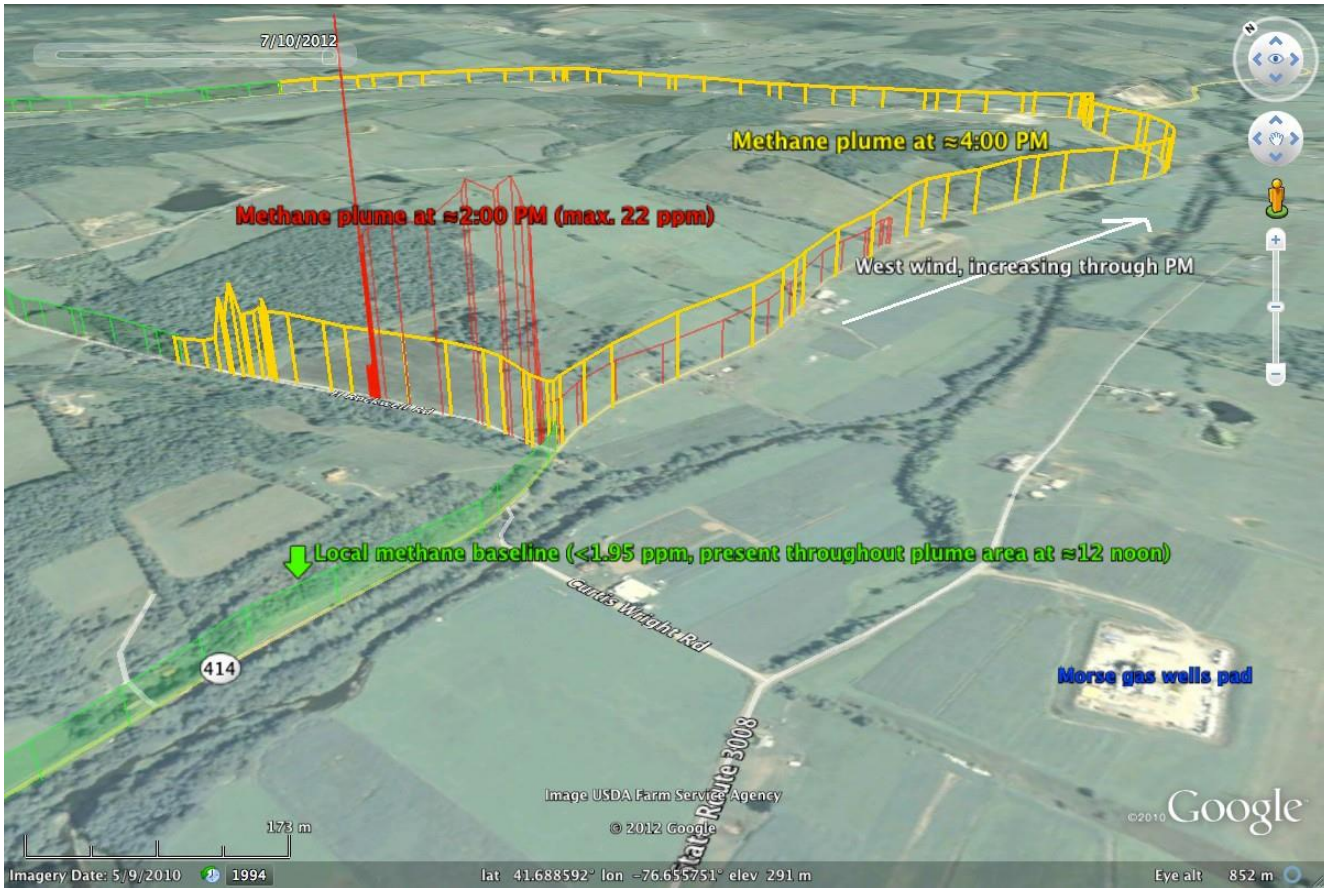
The CRDS instrument is extremely sensitive, runs continuously, and is robust. Consequently the unit quickly generates large volumes of highly reliable methane measurements on a continuous basis. During the one-day area survey reported here, the instrument generated 7,697 methane measurements. In combination with similar quantities of data from prior surveys in the eastern Marcellus Shale region, GSI has determined that a reliable (99.99% confidence level) upper bound for background methane levels in ground level air is 1.95 parts per million (ppm). GSI also has identified thousands of gas leaks in commercial pipelines in a variety of settings and based on that experience has concluded that CRDS measured levels of methane in excess of 2.05 ppm reliably indicate a natural gas leak in the surrounding area. Based on these findings, GSI interprets methane levels above 1.95 ppm as presumptive, and above 2.05 ppm as highly probable methane contamination. There is potential for some biogenic sources to generate enough methane to cause such readings, but such potential biogenic sources are usually readily identifiable, and limited in both extent and intensity in comparison to fugitive natural gas from wells or infrastructure. When more definitive evidence is needed, gas samples are collected and analyzed for isotopic composition for comparison to similar data for suspected sources of contaminating gas.

The areas in Leroy, Granville, and Franklin Townships surveyed and reported here had background levels and variations typical for the region, the lowest methane reading being 1.674 ppm (nominal accuracy of the CRDS is 0.001 ppm). Some areas of elevated methane in the air occurred near areas on farms with long-term animal manure loads. No elevated methane levels were found for carcass handling, and other agricultural areas that might be conventionally considered suspect for biogenic methane production. Interestingly no elevated methane levels were measured at the nearest access (200 meters) to the natural gas well pad (Morse 3H and 5H wells) within the area covered by this survey. This would seem a reasonable finding given the well is new, with limited and new infrastructure, and there was no wind during sampling in that area. With no wind and the low density of methane (half that of air), any gas leaks comprised primarily of methane would likely rise directly upward and go undetected without adequately close access to the vicinity of the leak.

Elevated methane levels, however, were detected as soon as the instrument was activated at the junction of Routes 414 and 514. All of the initial 157 readings were above 1.95 ppm, 152 were above 2.00 ppm. Such sustained levels above 1.95 indicate a fugitive methane source upwind. An initial drive and walk survey along and near Route 514 covering approximately 2 kilometers to the north and back indicated no methane above reasonable background levels. The initially observed elevated readings at the junction of Routes 414 and 514 had diminished when the instrument was returned to the location just over one hour later.

A driving survey west on Rt 414 (0.6 kilometers), south on Cross Road (0.5 kilometers), and west on South Side Road (2.2 kilometers) again revealed no elevated methane levels, as did a walking survey upslope from South Side Road, downwind from the Morse gas well pad.

Upon descending to the banks of Towanda Creek, methane levels rose above baseline in the vicinity of the creek banks. Random sampling at three locations showed maximum methane levels immediately above the soil surface of 133, 391, and 713 ppm. At the time of the observations there was no basis for inferring whether the methane was more likely biogenic or fugitive thermogenic gas. Methane levels were slightly elevated over most of the surveyed area along the creek.



The next leg of the survey involved a return east on South Side Road, then north across the bridge, and west along Rt 414 (2.2 kilometers) and north on H Rockwell Road (1 kilometer) (below red methane spike in image above). Methane levels were normal (indicated by green methane level markers in image above) until reaching H Rockwell Road, where slightly elevated levels were again encountered (average of 32 readings = 2.068, range = 1.967 to 2.184ppm) northbound along the first approximately 500 meters of that road. About an hour later, on the return trip south on H Rockwell Road and east on Rt 414 the methane levels (red methane level markers in image above) had risen substantially and the affected area expanded south and east. Methane levels began to rise relatively suddenly about 500meters north of Rt 414 from 2.01 ppm to a maximum of 21.979 ppm, then settled into a range of 10 to 14 ppm. The area of elevated methane levels had expanded to the south and east as indicated by measurements along Rt 414 showing levels descending from 4.620 ppm at H Rockwell Road to 2.049 ppm approximately 1 kilometer to the east. Another survey pass was made through the area approximately 1 hour 50 minutes later driving eastbound on Rt 414 (yellow methane level markers in image above). The elevated methane levels were then found to have expanded to cover an area from Rockwell Road east along Rt 414 for 2.8 kilometers then north along Rt 514 (2.8 kilometers) at an overall average concentration of 3.8 ppm. The data clearly indicated that one or more methane emissions were present and releasing substantial amounts of methane into the atmosphere probably within 500 meters to the north of Rt 414, near and to the west of Rockwell Road along with other possible emissions occurring or developing within the area enclosed by Rockwell Road and Rts 414 and 514. The measured plume covered an area of approximately 4.2 square kilometers, however, methane data and wind direction indicate the plume probably extended considerably farther to the south and east. Time was insufficient to measure the full extent of the plume to the south and east.

Gas was reported to have been bubbling up in Towanda Creek beneath the Cross Road bridge. The bridge was visited to view the gas bubbling, if present. Upon arrival the bubbling proved to be relatively easily observed. Batches of bubbles were rising to the surface at consistent time intervals and locations, fairly regularly spaced along a line running roughly east-northeast for the entire distance visible from the bridge, about 100 meters west to a somewhat shorter distance east. The directional orientation of the line of bubbles and regular spacing between bubbling points suggested association with a local fault or related subsurface structure. The total volume of bubbles per batch was very roughly estimated to be at least 300 cubic centimeters. Over the visible length of the bubble line the bubbling was nearly always occurring at one or more of the locations. Hence, the observed bubbling area was estimated to have been releasing at least 300 cubic centimeters per second, or 18 liters per minute, or 38 cubic feet per hour.

The volume and spatial distribution of the bubbling locations make other potential explanations, e.g., a biogenic methane source in the creek bottom, seem implausible. When the direction of the bubbling line under the bridge was extended to the west-southwest, it intersected the area where methane had been measured in the creek bank soils earlier in the day, suggesting the possibility that methane emissions may have been occurring along a fault line, but due to lack of access and time there was no opportunity to evaluate this possibility.

It is important and useful to note that the gas released in the creek under the bridge could not be confirmed to be methane with the CRDS instrument due to wind conditions and no access to the bubbling points in the creek due to the high elevation of the deck of the bridge. Further, there is the possibility that the gas in the bubbles is comprised of other gases besides methane. This could presumably be due the air normally present in local faults and fractures being displaced by methane intruding under pressure. If this were the case, then the methane content of the gas in the bubbles would initially contain little or no thermogenic methane, with relatively sudden increase in methane concentration once intruding methane effectively purges the fracture

The data available from 3 survey drive-by passes over this area spanned a period of 3.5 hours. Assuming the measured concentration is consistent from the ground surface to 2 meters above, the volume of ground level air in the plume area is 4.2 square kilometers X 2m = 4,200,000 square meters x 2m = 8,400,000 cubic meters. A methane concentration increase of 1.8 ppm would require 15.2 cubic meters of methane. Given the 3.5 hours over which this accumulation occurred, the implied emission rate is 4.3 cubic meters, or 150 cubic feet per hour. This, however, is a major underestimation of the likely volume of gas being released in the identified plume. Methane is a low-density gas, about half the density of air. Consequently, methane will tend to rise in the air relatively rapidly and the lowest methane concentrations in the vicinity of a surface methane emission will be expected to occur at ground level. It follows, therefore, that an estimate of the likely methane emission rate in the identified plume area that includes the vertical extent of the plume would be orders of magnitude greater than the above estimate (150 cubic feet per hour) based on ground level methane only. Application of air contaminant diffusion models appropriate to estimating the full-height methane emission rate was beyond the scope of this effort. The most definitive and reliable approach would be direct investigation of methane emissions through water and soil surfaces using the CRDS instrument and appropriate related equipment. However, this approach requires direct access to the properties on which the methane emissions are occurring, which could not be obtained for this effort. Further, emissions through soil surfaces typically are invisible and may occur for prolonged periods with no recognition until vegetation is damaged or killed by asphyxiation of the roots. Hence, many property owners may be heavily impacted but be unaware, and, therefore, reluctant to participant in methane emission survey efforts.

In summary, the methane survey data collected on 8 June 2012 in parts of Leroy, Granville, and Franklin Townships, Bradford County, Pennsylvania indicated one or more substantial methane emissions were occurring in an area centered roughly on the intersection of H Rockwell Road and Route 414. A ground level plume was detected that increased in area substantially over a period of 3.5 hours, which, when expanded to account for above ground level methane, suggests large amounts of methane were being emitted to the atmosphere. Heavily methane contaminated residential water wells occurred in and around the same area, and documentation indicated heavy contamination had existed for at least several months. Bubbling gas in Towanda Creek suggested fugitive gas from shale gas wells might be travelling through faults and fractures, which also carry local ground water, hence, impact local water wells. Collectively the data and observations suggest natural gas has pervaded an extensive subsurface area beyond the area where elevated ground-level methane was found during this survey effort. If that is correct, then more surface emissions should be expected. The issues and concerns presented in this report require more thorough investigation for confirmation and quantification.

Appendix H

ENERGY

Methane leaks erode green credentials of natural gas

Losses of up to 9% show need for broader data on US gas industry's environmental impact.

BY JEFF TOLLEFSON

Scientists are once again reporting alarmingly high methane emissions from an oil and gas field, underscoring questions about the environmental benefits of the boom in natural-gas production that is transforming the US energy system.

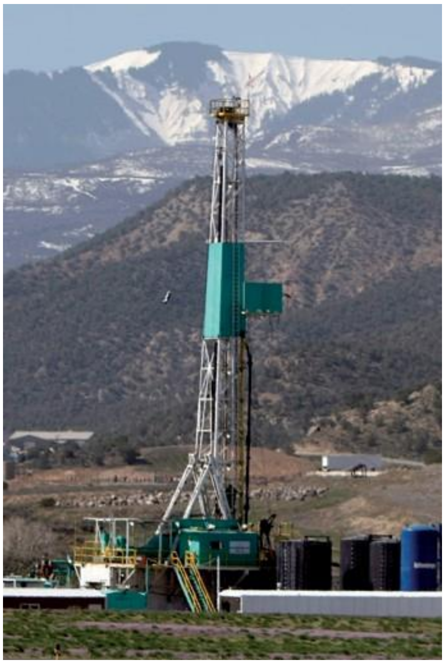
The researchers, who hold joint appointments with the National Oceanic and Atmospheric Administration (NOAA) and the University of Colorado in Boulder, first sparked concern in February 2012 with a study[1] suggesting that up to 4% of the methane produced at a field near Denver was escaping into the atmosphere. If methane — a potent greenhouse gas — is leaking from fields across the country at similar rates, it could be offsetting much of the climate benefit of the ongoing shift from coal- to gas-fired plants for electricity generation.

Industry officials and some scientists contested the claim, but at an American Geophysical Union (AGU) meeting in San Francisco, California, last month, the research team reported new Colorado data that support the earlier work, as well as preliminary results from a field study in the Uinta Basin of Utah suggesting even higher rates of methane leakage — an eye-popping 9% of the total production. That figure is nearly double the cumulative loss rates estimated from industry data — which are already higher in Utah than in Colorado.

"We were expecting to see high methane levels, but I don't think anybody really comprehended the true magnitude of what we would see," says Colm Sweeney, who led the aerial component of the study as head of the aircraft programme at NOAA's Earth System Research Laboratory in Boulder.

Whether the high leakage rates claimed in Colorado and Utah are typical across the US natural-gas industry remains unclear. The NOAA data represent a "small snapshot" of a much larger picture that the broader scientific community is now assembling, says Steven Hamburg, chief scientist at the Environmental Defense Fund (EDF) in Boston, Massachusetts.

The NOAA researchers collected their data in February as part of a broader analysis of air pollution in the Uinta Basin, using ground-based equipment and an aircraft to make detailed measurements of various pollutants, including methane concentrations. The researchers used atmospheric modelling to calculate the level of methane emissions required to reach those concentrations, and then compared that with industry data on gas production to obtain the percentage escaping into the atmosphere through venting and leaks.



Natural-gas wells such as this one in Colorado are increasingly important to the US energy supply.

L. DAVID ZALUBOWSKI/AP

The results build on those of the earlier Colorado study[1] in the Denver–Julesburg Basin, led by NOAA scientist Gabrielle Pétron (see *Nature* **482,** 139–140; 2012). That study relied on pollution measurements taken in 2008 on the ground and from a nearby tower, and estimated a leakage rate that was about twice as high as official figures suggested. But the team's methodology for calculating leakage — based on chemical analysis of the pollutants — remains in dispute. Michael Levi, an energy analyst at the Council on Foreign Relations in New York, published a peer-reviewed comment[2] questioning the findings and presenting an alternative interpretation of the data that would align overall leakage rates with previous estimates.

Pétron and her colleagues have a defence of the Colorado study in press[3], and at the AGU meeting she discussed a new study of the Denver–Julesburg Basin conducted with scientists at Picarro, a gas-analyser manufacturer based in Santa Clara, California. That study relies on carbon isotopes to differentiate between industrial emissions and methane from cows and feedlots, and the preliminary results line up with their earlier findings.

A great deal rides on getting the number right. A study[4] published in April by scientists at the EDF and Princeton University in New Jersey suggests that shifting to natural gas from coal-fired generators has immediate climatic benefits as long as the cumulative leakage rate from natural-gas production is below 3.2%; the benefits accumulate over time and are even larger if the gas plants replace older coal plants. By comparison, the authors note that the latest estimates from the US Environmental Protection Agency (EPA) suggest that 2.4% of total natural-gas production was lost to leakage in 2009.

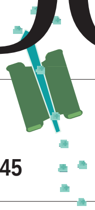
To see if that number holds up, the NOAA scientists are also taking part in a comprehensive assessment of US natural-gas emissions, conducted by the University of Texas at Austin and the EDF, with various industry partners. The initiative will analyse emissions from the production, gathering, processing, long-distance transmission and local distribution of natural gas, and will gather data on the use of natural gas in the transportation sector. In addition to scouring through industry data, the scientists are collecting field measurements at facilities across the country. The researchers expect to submit the first of these studies for publication by February, and say that the others will be complete within a year.

In April, the EPA issued standards intended to reduce air pollution from hydraulic-fracturing operations — now standard within the oil and gas industry — and advocates say that more can be done, at the state and national levels, to reduce methane emissions. "There are clearly opportunities to reduce leakage," says Hamburg. ■

1. Pétron, G. *et al. J. Geophys. Res.* **117,** D04304 (2012).
2. Levi, M. A. *J. Geophys. Res.* **117,** D21203 (2012).
3. Pétron, G. *et al. J. Geophys. Res.* (in the press).
4. Alvarez, R. A., Pacala, S. W. Winebrake, J. J., Chameides, W. L. & Hamburg, S. P. *Proc. Natl Acad. Sci. USA* **109,** 6435–6440 (2012).

Appendix I

NEWS IN FOCUS



J. SARTORE/NATIONAL GEOGRAPHIC STOCK

Natural-gas operations in areas such as Wyoming's Jonah Field could release far more methane into the atmosphere than previously thought.

CLIMATE CHANGE

Air sampling reveals high emissions from gas field

Methane leaks during production may offset climate benefits of natural gas.

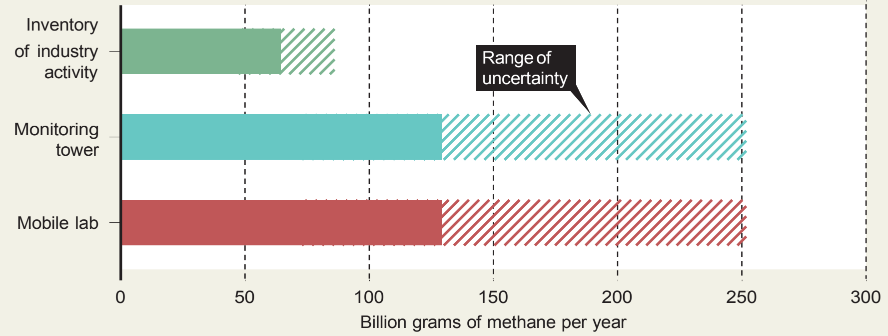
BY JEFF TOLLEFSON

When US government scientists began sampling the air from a tower north of Denver, Colorado, they expected urban smog — but not strong whiffs of what looked like natural gas. They eventually linked the mysterious pollution to a nearby natural-gas field, and their investigation has now produced the first hard evidence that the cleanest-burning fossil fuel might not be much better than coal when it comes to climate change.

Led by researchers at the National Oceanic and Atmospheric Administration (NOAA) and the University of Colorado, Boulder, the study estimates that natural-gas producers in an area known as the Denver-Julesburg Basin are losing about 4% of their gas to the atmosphere — not including additional losses in the pipeline and distribution system. This is more than double the official inventory, but roughly in line with estimates made in 2011 that have been challenged by industry. And because methane is some 25 times more efficient than carbon dioxide at trapping heat in the atmosphere, releases of that magnitude ▶

A LOSING BATTLE

Estimates of methane losses from gas felds near Denver, Colorado, based on air sampling differ considerably from calculations based on industry activity.



G. PÉTRON *ET AL. J. GEOPHYS. RES.*

▶ could effectively offset the environmental edge that natural gas is said to enjoy over other fossil fuels.

"If we want natural gas to be the cleanest fossil fuel source, methane emissions have to be reduced," says Gabrielle Pétron, an atmospheric scientist at NOAA and at the University of Colorado in Boulder, and first author on the study, currently in press at the *Journal of Geophysical Research*. Emissions will vary depending on the site, but Pétron sees no reason to think that this particular basin is unique. "I think we seriously need to look at natural-gas operations on the national scale."

The results come as a natural-gas boom hits the United States, driven by a technology known as hydraulic fracturing, or 'fracking', that can crack open hard shale formations and release the natural gas trapped inside. Environmentalists are worried about effects such as water pollution, but the US government is enthusiastic about fracking. In his State of the Union address last week, US President Barack Obama touted natural gas as the key to boosting domestic energy production.

LACK OF DATA

Natural gas emits about half as much carbon dioxide as coal per unit of energy when burned, but separate teams at Cornell University in Ithaca, New York, and at the US Environmental Protection Agency (EPA) concluded last year that methane emissions from shale gas are much larger than previously thought. The industry and some academics branded those findings as exaggerated, but the debate has been marked by a scarcity of hard data.

"It's great to get some actual numbers from the field," says Robert Howarth, a Cornell researcher whose team raised concerns about methane emissions from shale-gas drilling in a pair of papers, one published in April last year and another last month (R. W. Howarth *et al. Clim. Change Lett*. **106,** 679–690; 2011; R. W. Howarth *et al. Clim. Change* in the press). "I'm not looking for vindication here, but [the NOAA] numbers are coming in very close to ours, maybe a little higher," he says.

Natural gas might still have an advantage over coal when burned to create electricity, because gas-fired power plants tend to be newer and far more efficient than older facilities that provide the bulk of the country's coal-fired generation. But only 30% of US gas is used to produce electricity, Howarth says, with much of the rest being used for heating, for which there is no such advantage.

ON THE SCENT

The first clues appeared in 2007, when NOAA researchers noticed occasional plumes of pollutants including methane, butane and propane in air samples taken from a 300-metre-high atmospheric monitoring tower north of Denver. The NOAA researchers worked out the general direction that the pollution was coming from by monitoring winds, and in 2008, the team took advantage of new equipment and drove around the region, sampling the air in real time. Their readings led them to the Denver-Julesburg Basin, where more than 20,000 oil and gas wells have been drilled during the past four decades.

"A big part of it is just raw gas that is leaking from the infrastructure."

Most of the wells in the basin are drilled into 'tight sand' formations that require the same fracking technology being used in shale formations. This process involves injecting a slurry of water, chemicals and sand into wells at high pressure to fracture the rock and create veins that can carry trapped gas to the well. Afterwards, companies need to pump out the fracking fluids, releasing bubbles of dissolved gas as well as burps of early gas production. Companies typically vent these early gases into the atmosphere for up to a month or more until the well hits its full stride, at which point it is hooked up to a pipeline.

➲ NATURE.COM
Should fracking stop?
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The team analysed the ratios of various pollutants in the air samples and then tied that chemical fingerprint back to emissions from gas-storage tanks built to hold liquid petroleum gases before shipment. In doing so, they were able to work out the local emissions that would be necessary to explain the concentrations that they were seeing in the atmosphere (see 'A losing battle'). Some of the emissions come from the storage tanks, says Pétron, "but a big part of it is just raw gas that is leaking from the infrastructure". Their range of 2.3–7.7% loss, with a best guess of 4%, is slightly higher than Cornell's estimate of 2.2–3.8% for shale-gas drilling and production. It is also higher than calculations by the EPA, which revised its methodology last year and roughly doubled the official US inventory of emissions from the natural-gas industry over the past decade. Howarth says the EPA methodology translates to a 2.8% loss.

The Cornell group had estimated that 1.9% of the gas produced over the lifetime of a typical shale-gas well escapes through fracking and well completion alone. NOAA's study doesn't differentiate between gas from fracking and leaks from any other point in the production process, but Pétron says that fracking clearly contributes to some of the gas her team measured.

Capturing and storing gases that are being vented during the fracking process is feasible, but industry says that these measures are too costly to adopt. An EPA rule that is due out as early as April would promote such changes by regulating emissions from the gas fields.

Officials with America's Natural Gas Alliance, based in Washington DC, say that the study is difficult to evaluate based on a preliminary review, but in a statement to *Nature* they add that "the findings raise questions and warrant a closer examination by the scientific community". Environmental groups are pushing the EPA to strengthen pollution controls in the pending rule, but industry is pushing to relax many of the requirements. Many companies are already improving their practices and reducing emissions throughout the country, either voluntarily or by regulation, the alliance says.

Not all studies support the higher methane numbers. Sergey Paltsev, assistant director for economic research at the Massachusetts Institute of Technology Energy Initiative in Cambridge, and his colleagues are gathering information about industry practices for a study on shale-gas emissions. He says that their figures are likely to come in well below even the lower EPA estimate. He calls the NOAA results "surprising" and questions how representative the site is.

Pétron says that more studies are needed using industry inventories and measurements of atmospheric concentrations. "We will never get the same numbers," she says, "but if we can get close enough that our ranges overlap in a meaningful way, then we can say we understand the process." ■

Appendix J

Anthropogenic emissions of methane in the United States

Scot M. Miller[a,1], Steven C. Wofsy[a], Anna M. Michalak[b], Eric A. Kort[c], Arlyn E. Andrews[d], Sebastien C. Biraud[e], Edward J. Dlugokencky[d], Janusz Eluszkiewicz[f], Marc L. Fischer[g], Greet Janssens-Maenhout[h], Ben R. Miller[i], John B. Miller[i], Stephen A. Montzka[d], Thomas Nehrkorn[f], and Colm Sweeney[i]

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Edited by Mark H. Thiemens, University of California, San Diego, La Jolla, CA, and approved October 18, 2013 (received for review August 5, 2013)

This study quantitatively estimates the spatial distribution of anthropogenic methane sources in the United States by combining comprehensive atmospheric methane observations, extensive spatial datasets, and a high-resolution atmospheric transport model. Results show that current inventories from the US Environmental Protection Agency (EPA) and the Emissions Database for Global Atmospheric Research underestimate methane emissions nationally by a factor of ∼1.5 and ∼1.7, respectively. Our study indicates that emissions due to ruminants and manure are up to twice the magnitude of existing inventories. In addition, the discrepancy in methane source estimates is particularly pronounced in the south-central United States, where we find total emissions are ∼2.7 times greater than in most inventories and account for 24 ± 3% of national emissions. The spatial patterns of our emission fluxes and observed methane–propane correlations indicate that fossil fuel extraction and refining are major contributors (45 ± 13%) in the south-central United States. This result suggests that regional methane emissions due to fossil fuel extraction and processing could be 4.9 ± 2.6 times larger than in EDGAR, the most comprehensive global methane inventory. These results cast doubt on the US EPA's recent decision to downscale its estimate of national natural gas emissions by 25–30%. Overall, we conclude that methane emissions associated with both the animal husbandry and fossil fuel industries have larger greenhouse gas impacts than indicated by existing inventories.

climate change policy | geostatistical inverse modeling

Methane (CH_4) is the second most important anthropogenic greenhouse gas, with approximately one third the total radiative forcing of carbon dioxide (1). CH_4 also enhances the formation of surface ozone in populated areas, and thus higher global concentrations of CH_4 may significantly increase ground-level ozone in the Northern Hemisphere (2). Furthermore, methane affects the ability of the atmosphere to oxidize other pollutants and plays a role in water formation within the stratosphere (3).

Atmospheric concentrations of CH_4 [∼1,800 parts per billion (ppb)] are currently much higher than preindustrial levels (∼680–715 ppb) (1, 4). The global atmospheric burden started to rise rapidly in the 18th century and paused in the 1990s. Methane levels began to increase again more recently, potentially from a combination of increased anthropogenic and/or tropical wetland emissions (5–7). Debate continues, however, over the causes behind these recent trends (7, 8).

Anthropogenic emissions account for 50–65% of the global CH_4 budget of ∼395–427 teragrams of carbon per year (TgC·y)$^{-1}$ (526–569 Tg CH_4) (7, 9). The US Environmental Protection Agency (EPA) estimates the principal anthropogenic sources in the United States to be (in order of importance) (*i*) livestock (enteric fermentation and manure management), (*ii*) natural gas production and distribution, (*iii*) landfills, and (*iv*) coal mining (10). EPA assesses human-associated emissions in the United States in 2008 at 22.1 TgC, roughly 5% of global emissions (10).

The amount of anthropogenic CH_4 emissions in the US and attributions by sector and region are controversial (Fig. 1). Bottom-up inventories from US EPA and the Emissions Database for Global Atmospheric Research (EDGAR) give totals ranging from 19.6 to 30 TgC·y^{-1} (10, 11). The most recent EPA and EDGAR inventories report lower US anthropogenic emissions compared with previous versions (decreased by 10% and 35%, respectively) (10, 12); this change primarily reflects lower, revised emissions estimates from natural gas and coal production Fig. S1. However, recent analysis of CH_4 data from aircraft estimates a higher budget of 32.4 ± 4.5 TgC·y^{-1} for 2004 (13). Furthermore, atmospheric observations indicate higher emissions in natural gas production areas (14–16); a steady 20-y increase in the number of US wells and newly-adopted horizontal drilling techniques may have further increased emissions in these regions (17, 18).

These disparities among bottom-up and top-down studies suggest much greater uncertainty in emissions than typically reported. For example, EPA cites an uncertainty of only ±13% for the for United States (10). Independent assessments of bottom-up inventories give error ranges of 50–100% (19, 20), and

Significance

Successful regulation of greenhouse gas emissions requires knowledge of current methane emission sources. Existing state regulations in California and Massachusetts require ∼15% greenhouse gas emissions reductions from current levels by 2020. However, government estimates for total US methane emissions may be biased by 50%, and estimates of individual source sectors are even more uncertain. This study uses atmospheric methane observations to reduce this level of uncertainty. We find greenhouse gas emissions from agriculture and fossil fuel extraction and processing (i.e., oil and/or natural gas) are likely a factor of two or greater than cited in existing studies. Effective national and state greenhouse gas reduction strategies may be difficult to develop without appropriate estimates of methane emissions from these source sectors.

Author contributions: S.M.M., S.C.W., and A.M.M. designed research; S.M.M., A.E.A., S.C.B., E.J.D., J.E., M.L.F., G.J.-M., B.R.M., J.B.M., S.A.M., T.N., and C.S. performed research; S.M.M. analyzed data; S.M.M., S.C.W., A.M.M., and E.A.K. wrote the paper; A.E.A., S.C.B., E.J.D., M.L.F., B.R.M., J.B.M., S.A.M., and C.S. collected atmospheric methane data; and J.E. and T.N. developed meteorological simulations using the Weather Research and Forecasting model.

The authors declare no conflict of interest.

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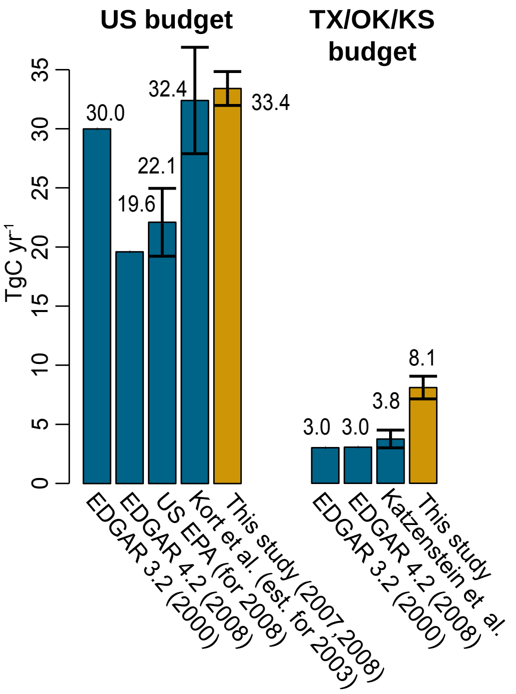

Fig. 1. US anthropogenic methane budgets from this study, from previous top-down estimates, and from existing emissions inventories. The south-central United States includes Texas, Oklahoma, and Kansas. US EPA estimates only national, not regional, emissions budgets. Furthermore, national budget estimates from EDGAR, EPA, and Kort et al. (13) include Alaska and Hawaii whereas this study does not.

values from Kort et al. are 47 ± 20% higher than EPA (13). Assessments of CH_4 sources to inform policy (e.g., regulating emissions or managing energy resources) require more accurate, verified estimates for the United States.

This study estimates anthropogenic CH_4 emissions over the United States for 2007 and 2008 using comprehensive CH_4 observations at the surface, on telecommunications towers, and from aircraft, combined with an atmospheric transport model and a geostatistical inverse modeling (GIM) framework. We use auxiliary spatial data (e.g., on population density and economic activity) and leverage concurrent measurements of alkanes to help attribute emissions to specific economic sectors. The work provides spatially resolved CH_4 emissions estimates and associated uncertainties, as well as information by source sector, both previously unavailable.

Model and Observation Framework

We use the Stochastic Time-Inverted Lagrangian Transport model (STILT) to calculate the transport of CH_4 from emission points at the ground to measurement locations in the atmosphere (21). STILT follows an ensemble of particles backward in time, starting from each observation site, using wind fields and turbulence modeled by the Weather Research and Forecasting (WRF) model (22). STILT derives an influence function ("footprint," units: ppb CH_4 per unit emission flux) linking upwind emissions to each measurement. Inputs of CH_4 from surface sources along the ensemble of back-trajectories are averaged to compute the CH_4 concentration for comparison with each observation.

We use observations for 2007 and 2008 from diverse locations and measurement platforms. The principal observations derive from daily flask samples on tall towers (4,984 total observations) and vertical profiles from aircraft (7,710 observations). Tower-based observations are collected as part of the National Oceanic and Atmospheric (NOAA)/Department of Energy (DOE) cooperative air sampling network, and aircraft-based data are obtained from regular NOAA flights (23), regular DOE flights (24), and from the Stratosphere-Troposphere Analyses of Regional Transport 2008 (START08) aircraft campaign (25); all data are publicly available from NOAA and DOE. These observations are displayed in Fig. 2 and discussed further in the SI Text (e.g., Fig. S2). We use a GIM framework (26, 27) to analyze the footprints for each of the 12,694 observations, and these footprints vary by site and with wind conditions. In aggregate, the footprints provide spatially resolved coverage of most of the continental United States, except the southeast coastal region (Fig. S3).

The GIM framework, using footprints and concentration measurements, optimizes CH_4 sources separately for each month of 2007 and 2008 on a 1° × 1° latitude–longitude grid for the United States. The contributions of fluxes from natural wetlands are modeled first and subtracted from the observed CH_4 (2.0 $TgC \cdot y^{-1}$ for the continental United States); these fluxes are much smaller than anthropogenic sources in the United States and thus would be difficult to independently constrain from atmospheric data (SI Text).

The GIM framework represents the flux distribution for each month using a deterministic spatial model plus a stochastic spatially correlated residual, both estimated from the atmospheric observations. The deterministic component is given by a weighted linear combination of spatial activity data from the EDGAR 4.2 inventory; these datasets include any economic or demographic data that may predict the distribution of CH_4 emissions (e.g., gas production, human and ruminant population densities, etc.). Both the selection of the activity datasets to be retained in the model and the associated weights (emission factors) are optimized to best match observed CH_4 concentrations. Initially, seven activity datasets are included from EDGAR 4.2, (i) population, (ii) electricity production from power plants, (iii) ruminant population count, (iv) oil and conventional gas production, (v) oil refinery production, (vi) rice production, and (vii) coal production.

We select the minimum number of datasets with the greatest predictive ability using the Bayesian Information Criterion (BIC) (SI Text) (28). BIC numerically scores all combinations of available datasets based on how well they improve goodness of fit and applies a penalty that increases with the number of datasets retained.

The stochastic component represents sources that do not fit the spatial patterns of the activity data (Fig. S4). GIM uses

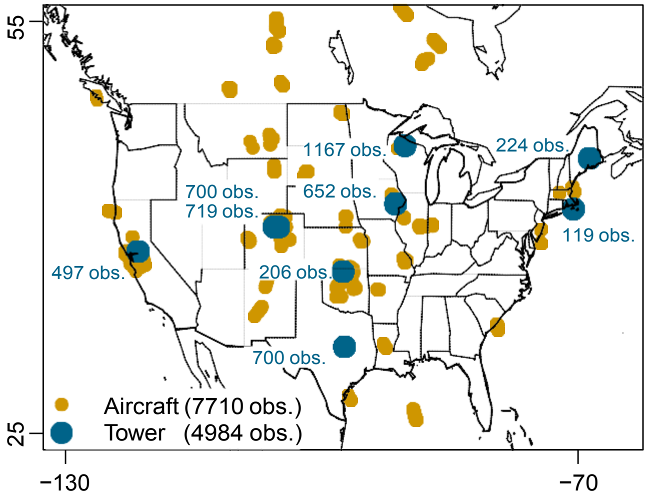

Fig. 2. CH_4 concentration measurements from 2007 and 2008 and the number of observations associated with each measurement type. Blue text lists the number of observations associated with each stationary tower measurement site.

a covariance function to describe the spatial and temporal correlation of the stochastic component and optimizes its spatial and temporal distribution simultaneously with the optimization of the activity datasets in the deterministic component (SI Text, Fig. S5) (26–28). Because of the stochastic component, the final emissions estimate can have a different spatial and temporal distribution from any combination of the activity data.

If the observation network is sensitive to a broad array of different source sectors and/or if the spatial activity maps are effective at explaining those sources, many activity datasets will be included in the deterministic model. If the deterministic model explains the observations well, the magnitude of CH_4 emissions in the stochastic component will be small, the assignment to specific sectors will be unambiguous, and uncertainties in the emissions estimates will be small. This result is not the case here, as discussed below (see Results).

A number of previous studies used top-down methods to constrain anthropogenic CH_4 sources from global (29–33) to regional (13–15, 34–38) scales over North America. Most regional studies adopted one of three approaches: use a simple box model to estimate an overall CH_4 budget (14), estimate a budget using the relative ratios of different gases (15, 37–39), or estimate scaling factors for inventories by region or source type (13, 34–36). The first two methods do not usually give explicit information about geographic distribution. The last approach provides information about the geographic distribution of sources, but results hinge on the spatial accuracy of the underlying regional or sectoral emissions inventories (40).

Here, we are able to provide more insight into the spatial distribution of emissions; like the scaling factor method above, we leverage spatial information about source sectors from an existing inventory, but in addition we estimate the distribution of emissions where the inventory is deficient. We further bolster attribution of regional emissions from the energy industry using the observed correlation of CH_4 and propane, a gas not produced by biogenic processes like livestock and landfills.

Results

Spatial Distribution of CH_4 Emissions. Fig. 3 displays the result of the 2-y mean of the monthly CH_4 inversions and differences from the EDGAR 4.2 inventory. We find emissions for the United States that are a factor of 1.7 larger than the EDGAR inventory. The optimized emissions estimated by this study bring the model closer in line with the observations (Fig. 4, Figs. S6 and S7). Posterior emissions fit the CH_4 observations [$R^2 = 0{:}64$, root mean square error (RMSE) = 31 ppb] much better than EDGAR v4.2 ($R^2 = 0{:}23$, RMSE = 49 ppb). Evidently, the spatial distribution of EDGAR sources is inconsistent with emissions patterns implied by the CH_4 measurements and associated footprints.

Several diagnostic measures preclude the possibility of major systematic errors in WRF–STILT. First, excellent agreement between the model and measured vertical profiles from aircraft implies little bias in modeled vertical air mixing (e.g., boundary-layer heights) (Fig. 4). Second, the monthly posterior emissions estimated by the inversion lack statistically significant seasonality (Fig. S8). This result implies that seasonally varying weather patterns do not produce detectable biases in WRF–STILT. SI Text discusses possible model errors and biases in greater detail.

CH_4 observations are sparse over parts of the southern and central East Coast and in the Pacific Northwest. Emissions estimates for these regions therefore rely more strongly on the deterministic component of the flux model, with weights constrained primarily by observations elsewhere. Therefore, emissions in these areas, including from coal mining, are poorly constrained (SI Text).

Contribution of Different Source Sectors. Only two spatial activity datasets from EDGAR 4.2 are selected through the BIC as meaningful predictors of CH_4 observations over the United States: population densities of humans and of ruminants (Table S1). Some sectors are eliminated by the BIC because emissions are situated far from observation sites (e.g., coal mining in West Virginia or Pennsylvania), making available CH_4 data insensitive to these predictors. Other sectors may strongly affect observed concentrations but are not selected, indicating that the spatial datasets from EDGAR are poor predictors for the distribution of observed concentrations (e.g., oil and natural gas extraction and oil refining). Sources from these sectors appear in the stochastic component of the GIM (SI Text).

The results imply that existing inventories underestimate emissions from two key sectors: ruminants and fossil fuel extraction and/or processing, discussed in the remainder of this section.

We use the optimized ruminant activity dataset to estimate the magnitude of emissions with spatial patterns similar to animal husbandry and manure. Our corresponding US budget of 12.7 ± 5.0 $TgC \cdot y^{-1}$ is nearly twice that of EDGAR and EPA (6.7 and 7.0, respectively). The total posterior emissions estimate over the northern plains, a region with high ruminant density but little fossil fuel extraction, further supports the ruminant estimate (Nebraska, Iowa, Wisconsin, Minnesota, and South Dakota). Our total budget for this region of 3.4 ± 0.7 compares with 1.5 $TgC \cdot y^{-1}$ in EDGAR. Ruminants and agriculture may also be

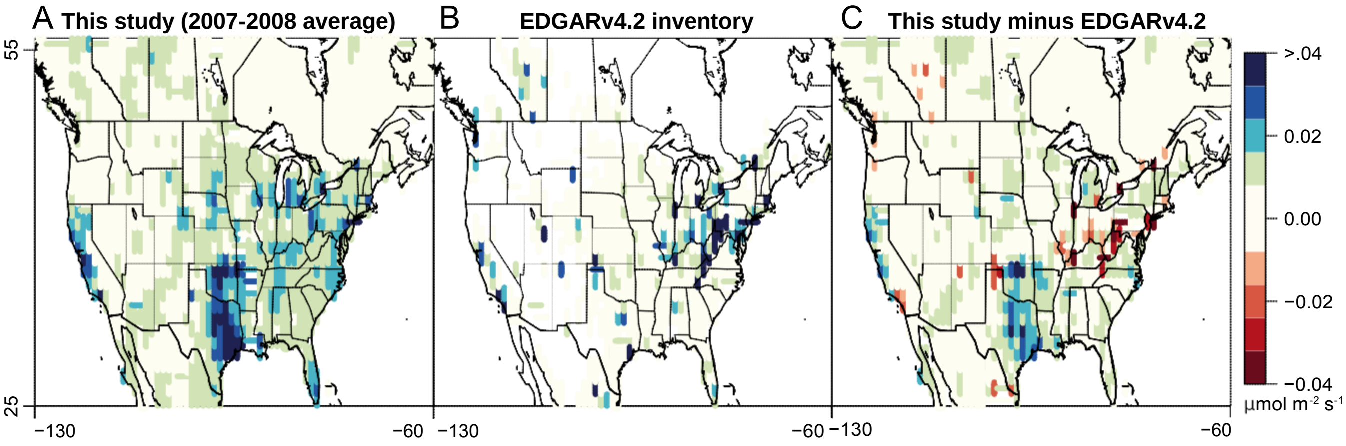

Fig. 3. The 2-y averaged CH_4 emissions estimated in this study (A) compared against the commonly used EDGAR 4.2 inventory (B and C). Emissions estimated in this study are greater than in EDGAR 4.2, especially near Texas and California.

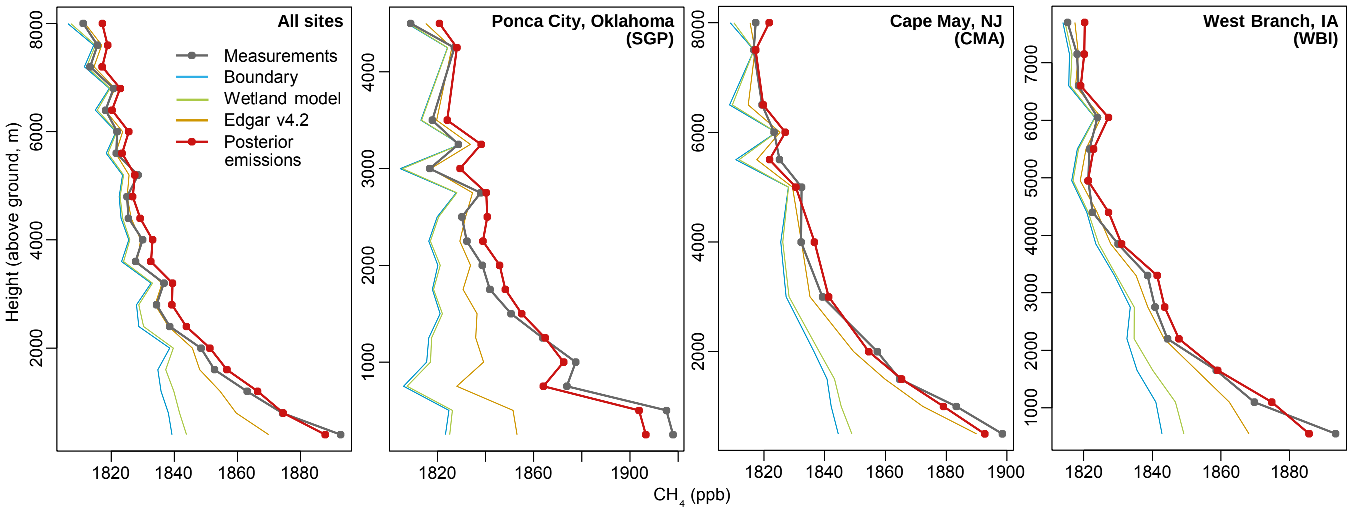

Fig. 4. A model–measurement comparison at several regular NOAA/DOE aircraft monitoring sites (averaged over 2007–2008). Plots include the measurements; the modeled boundary condition; the summed boundary condition and wetland contribution (from the Kaplan model); and the summed boundary, wetland, and anthropogenic contributions (from EDGAR v4.2 and the posterior emissions estimate).

partially responsible for high emissions over California (41). EDGAR activity datasets are poor over California (42), but several recent studies (34, 36–38, 41) have provided detailed top-down emissions estimates for the state using datasets from state agencies.

Existing inventories also greatly underestimate CH_4 sources from the south-central United States (Fig. 3). We find the total CH_4 source from Texas, Oklahoma, and Kansas to be 8.1 ± 0.96 $TgC\cdot y^{-1}$, a factor of 2.7 higher than the EDGAR inventory. These three states alone constitute ∼24 ± 3% of the total US anthropogenic CH_4 budget or 3.7% of net US greenhouse gas emissions [in CO_2 equivalents (10)].

Texas and Oklahoma were among the top five natural gas producing states in the country in 2007 (18), and aircraft observations of alkanes indicate that the natural gas and/or oil industries play a significant role in regional CH_4 emissions. Concentrations of propane (C_3H_8), a tracer of fossil hydrocarbons (43), are strongly correlated with CH_4 at NOAA/DOE aircraft monitoring locations over Texas and Oklahoma ($R^2 = 0{:}72$) (Fig. 5). Correlations are much weaker at other locations in North America ($R^2 = 0{:}11$ to 0.64).

We can obtain an approximate CH_4 budget for fossil-fuel extraction in the region by subtracting the optimized contributions associated with ruminants and population from the total emissions. The residual (Fig. S4C) represents sources that have spatial patterns not correlated with either human or ruminant density in EDGAR. Our budget sums to 3.7 ± 2.0 $TgC\cdot y^{-1}$, a factor of 4.9 ± 2.6 larger than oil and gas emissions in EDGAR v4.2 (0.75 $TgC\cdot y^{-1}$) and a factor of 6.7 ± 3.6 greater than EDGAR sources from solid waste facilities (0.55 $TgC\cdot y^{-1}$), the two major sources that may not be accounted for in the deterministic component. The population component likely captures a portion of the solid waste sources so this residual methane budget more likely represents natural gas and oil emissions than landfills. SI Text discusses in detail the uncertainties in this sector-based emissions estimate. We currently do not have the detailed, accurate, and spatially resolved activity data (fossil fuel extraction and processing, ruminants, solid waste) that would provide more accurate sectorial attribution.

Katzenstein et al. (2003) (14) were the first to report large regional emissions of CH_4 from Texas, Oklahoma, and Kansas; they cover an earlier time period (1999–2002) than this study. They used a box model and 261 near-ground CH_4 measurements taken over 6 d to estimate a total Texas–Oklahoma–Kansas CH_4 budget (from all sectors) of 3.8 ± 0.75 $TgC\cdot y^{-1}$. We revise their

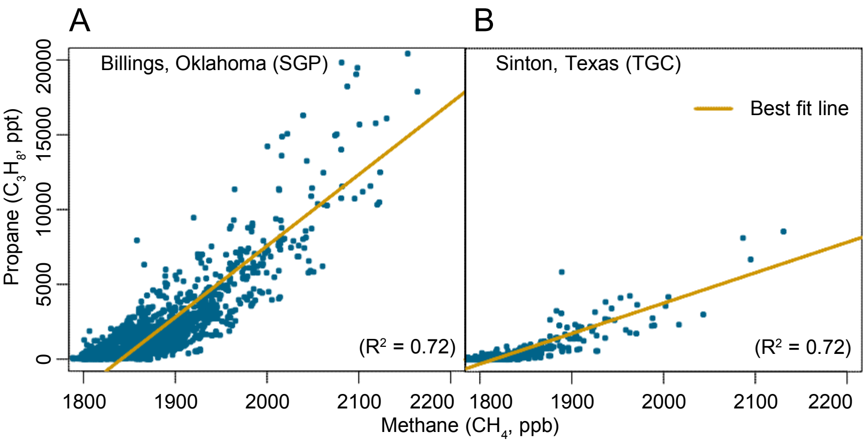

Fig. 5. Correlations between propane and CH_4 at NOAA/DOE aircraft observation sites in Oklahoma (A) and Texas (B) over 2007–2012. Correlations are higher in these locations than at any other North American sites, indicating large contributions of fossil fuel extraction and processing to CH_4 emitted in this region.

estimate upward by a factor of two based on the inverse model and many more measurements from different platforms over two full years of data. SI Text further compares the CH_4 estimate in Katzenstein et al. and in this study.

Discussion and Summary

This study combines comprehensive atmospheric data, diverse datasets from the EDGAR inventory, and an inverse modeling framework to derive spatially resolved CH_4 emissions and information on key source sectors. We estimate a mean annual US anthropogenic CH_4 budget for 2007 and 2008 of 33.4 ± 1.4 $TgC\cdot y^{-1}$ or ∼7–8% of the total global CH_4 source. This estimate is a factor of 1.5 and 1.7 larger than EPA and EDGAR v4.2, respectively. CH_4 emissions from Texas, Oklahoma, and Kansas alone account for 24% of US methane emissions, or 3.7% of the total US greenhouse gas budget.

The results indicate that drilling, processing, and refining activities over the south-central United States have emissions as much as 4.9 ± 2.6 times larger than EDGAR, and livestock operations across the US have emissions approximately twice that of recent inventories. The US EPA recently decreased its CH_4 emission factors for fossil fuel extraction and processing by 25–30% (for 1990–2011) (10), but we find that CH_4 data from across North America instead indicate the need for a larger adjustment of the opposite sign.

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1. Butler J (2012) The NOAA annual greenhouse gas index (AGGI). Available at http://www.esrl.noaa.gov/gmd/aggi/. Accessed November 4, 2013.
2. Fiore AM, et al. (2002) Linking ozone pollution and climate change: The case for controlling methane. Geophys Res Lett 29:1919.
3. Jacob D (1999) Introduction to Atmospheric Chemistry (Princeton Univ Press, Princeton).
4. Mitchell LE, Brook EJ, Sowers T, McConnell JR, Taylor K (2011) Multidecadal variability of atmospheric methane, 1000-1800 CE. J Geophys Res Biogeosci 116:G02007.
5. Dlugokencky EJ, et al. (2009) Observational constraints on recent increases in the atmospheric CH_4 burden. Geophys Res Lett 36:L18803.
6. Sussmann R, Forster F, Rettinger M, Bousquet P (2012) Renewed methane increase for five years (2007-2011) observed by solar FTIR spectrometry. Atmos Chem Phys 12: 4885–4891.
7. Kirschke S, et al. (2013) Three decades of global methane sources and sinks. Nat Geosci 6:813–823.
8. Wang JS, et al. (2004) A 3-D model analysis of the slowdown and interannual variability in the methane growth rate from 1988 to 1997. Global Biogeochem Cycles 18: GB3011.
9. Ciais P, et al. (2013) Carbon and Other Biogeochemical Cycles: Final Draft Underlying Scientific Technical Assessment (IPCC Secretariat, Geneva).
10. US Environmental Protection Agency (2013) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2011, Technical Report EPA 430-R-13-001 (Environmental Protection Agency, Washington).
11. Olivier JGJ, Peters J (2005) CO_2 from non-energy use of fuels: A global, regional and national perspective based on the IPCC Tier 1 approach. Resour Conserv Recycling 45:210–225.
12. European Commission Joint Research Centre, Netherlands Environmental Assessment Agency (2010) Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2. Available at http://edgar.jrc.ec.europa.eu. Accessed November 4, 2013.
13. Kort EA, et al. (2008) Emissions of CH_4 and N_2O over the United States and Canada based on a receptor-oriented modeling framework and COBRA-NA atmospheric observations. Geophys Res Lett 35:L18808.
14. Katzenstein AS, Doezema LA, Simpson IJ, Blake DR, Rowland FS (2003) Extensive regional atmospheric hydrocarbon pollution in the southwestern United States. Proc Natl Acad Sci USA 100(21):11975–11979.
15. Pétron G, et al. (2012) Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. J Geophys Res Atmos 117:D04304.
16. Karion A, et al. (2013) Methane emissions estimate from airborne measurements over a western United States natural gas field. Geophys Res Lett 40:4393–4397.
17. Howarth RW, Santoro R, Ingraffea A (2011) Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim Change 106:679–690.
18. US Energy Information Administration (2013) Natural Gas Annual 2011, Technical report (US Department of Energy, Washington).
19. National Research Council (2010) Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements (National Academies Press, Washington).
20. Dlugokencky EJ, Nisbet EG, Fisher R, Lowry D (2011) Global atmospheric methane: Budget, changes and dangers. Philos Trans A Math Phys Eng Sci 369(1943): 2058–2072.
21. Lin JC, et al. (2003) A near-field tool for simulating the upstream influence of atmospheric observations: The Stochastic Time-Inverted Lagrangian Transport (STILT) model. J Geophys Res Atmos 108(D16):4493.
22. Nehrkorn T, et al. (2010) Coupled Weather Research and Forecasting-Stochastic Time-Inverted Lagrangian Transport (WRF-STILT) model. Meteorol Atmos Phys 107:51–64.
23. NOAA ESRL (2013) Carbon Cycle Greenhouse Gas Group Aircraft Program. Available at http://www.esrl.noaa.gov/gmd/ccgg/aircraft/index.html. Accessed November 4, 2013.
24. Biraud SC, et al. (2013) A multi-year record of airborne CO_2 observations in the US southern great plains. Atmos Meas Tech 6:751–763.
25. Pan LL, et al. (2010) The Stratosphere-Troposphere Analyses of Regional Transport 2008 Experiment. Bull Am Meteorol Soc 91:327–342.
26. Kitanidis PK, Vomvoris EG (1983) A geostatistical approach to the inverse problem in groundwater modeling (steady state) and one-dimensional simulations. Water Resour Res 19:677–690.
27. Michalak A, Bruhwiler L, Tans P (2004) A geostatistical approach to surface flux estimation of atmospheric trace gases. J Geophys Res Atmos 109(D14):D14109.
28. Gourdji SM, et al. (2012) North American CO_2 exchange: Inter-comparison of modeled estimates with results from a fine-scale atmospheric inversion. Biogeosciences 9: 457–475.
29. Chen YH, Prinn RG (2006) Estimation of atmospheric methane emissions between 1996 and 2001 using a three-dimensional global chemical transport model. J Geophys Res Atmos 111(D10):D10307.
30. Meirink JF, et al. (2008) Four-dimensional variational data assimilation for inverse modeling of atmospheric methane emissions: Analysis of SCIAMACHY observations. J Geophys Res Atmos 113(D17):D17301.
31. Bergamaschi P, et al. (2009) Inverse modeling of global and regional CH4 emissions using SCIAMACHY satellite retrievals. J Geophys Res Atmos 114(D22):D22301.
32. Bousquet P, et al. (2011) Source attribution of the changes in atmospheric methane for 2006-2008. Atmos Chem Phys 11:3689–3700.
33. Monteil G, et al. (2011) Interpreting methane variations in the past two decades using measurements of CH_4 mixing ratio and isotopic composition. Atmos Chem Phys 11: 9141–9153.
34. Zhao C, et al. (2009) Atmospheric inverse estimates of methane emissions from central California. J Geophys Res Atmos 114(D16):D16302.
35. Kort EA, et al. (2010) Atmospheric constraints on 2004 emissions of methane and nitrous oxide in North America from atmospheric measurements and receptor-oriented modeling framework. J Integr Environ Sci 7:125–133.
36. Jeong S, et al. (2012) Seasonal variation of CH_4 emissions from central California. J Geophys Res 117:D11306.
37. Peischl J, et al. (2012) Airborne observations of methane emissions from rice cultivation in the Sacramento Valley of California. J Geophys Res Atmos 117(D24):D00V25.
38. Wennberg PO, et al. (2012) On the sources of methane to the Los Angeles atmosphere. Environ Sci Technol 46(17):9282–9289.
39. Miller JB, et al. (2012) Linking emissions of fossil fuel CO2 and other anthropogenic trace gases using atmospheric 14CO2. J Geophys Res Atmos 117(D8):D08302.
40. Law RM, Rayner PJ, Steele LP, Enting IG (2002) Using high temporal frequency data for CO_2 inversions. Global Biogeochem Cycles 16(4):1053.
41. Jeong S, et al. (2013) A multitower measurement network estimate of California's methane emissions. J Geophys Res Atmos, 10.1002/jgrd.50854.
42. Xiang B, et al. (2013) Nitrous oxide (N2O) emissions from California based on 2010 CalNex airborne measurements. J Geophys Res Atmos 118(7):2809–2820.
43. Koppmann R (2008) Volatile Organic Compounds in the Atmosphere (Wiley, Singapore).

Comments Received during the Public Review Period on the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013

Commenter: Roger Johnson

National Farmer's Union (NFU)

Comment: NFU appreciates the work EPA has undertaken to successfully inventory greenhouse gas (GHG) emissions and fluxes in the U.S., summarize and present them by source category and sector. Collecting and presenting this information is extremely important because the accumulation of GHGs in the atmosphere resulting from human activity is expected to impact global climate patterns. NFU's policy, which is subject to annual review by NFU membership, states, "NFU is concerned about the effects of climate change and believes further research and analysis is necessary to determine its actual and potential impacts."

Family farmers and ranchers are faced with many perils in a changing climate including mounting weather volatility, changes in water resources, increasing heat stress for crops and livestock and pressure from invasive species, pests, and weeds. Producers across the U.S. are already feeling the impact of increasing weather volatility, one among many of the hazards to agriculture attendant to climate change.

Extreme weather events limit workable field days, exacerbate productivity and environmental issues related to soil erosion, and harm the economy by increasing crop insurance claims. Potential impacts on water resources are also of grave concern because adequate water is absolutely essential to farmers' ability to produce the crops upon which we all rely.

Taken together, the challenges to agriculture inherent to climate change could severely increase food prices and significantly disrupt our ability to provide adequate food for a growing world population.

These challenges make clear the importance of examining factors contributing to climate change so that plans for resiliency and mitigation can be established. NFU appreciates EPA's efforts toward making such information accessible through the Inventory.

NFU appreciates EPA's work inventorying GHG emissions as a step toward facilitating family farmers' participation in enhancing climate resilience.

Commenter: David Lyon

Environmental Defense Fund (EDF)

Comment: EDF supports the use of IPCC Fourth Assessment Report (AR4) global warming potential (GWP) values in the 2015 Inventory. The AR4 GWP values are based on updated scientific knowledge of the relative climate impacts of individual greenhouse gases. To reflect further advancement in climate science, future inventories should use IPCC Fifth Assessment Report (AR5) GWP values as soon as allowed by the UNFCCC reporting guidelines.

Comment: The proposed revisions to the Greenhouse Gas Reporting Program (GHGRP) Subpart W include a requirement for emissions reporting from oil well completions and workovers with hydraulic fracturing. Once that data is available, a methodology similar to the one currently used in the Inventory to estimate emissions from gas well completions with hydraulic fracturing could be used for oil well completions. Until that time, EDF recommends that oil well completion emission factors in the Inventory are updated with currently available data such as the sources discussed in EDF's peer review comments on the EPA White Paper Oil and Natural Gas Sector Hydraulically Fractured Oil Well Completions and Associated Gas during Ongoing Production. Based on a conservatively low assumption of 7.7 tons methane per completion event and 75% of new oil wells using hydraulic fracturing, emissions would be over a factor of 400X higher than the current Inventory estimate for oil well completions, which is based on an emission factor inappropriate for hydraulically-fractured oil wells.

Comment: Two recent national studies of methane emissions from natural gas production sector pneumatic controllers have reported that the Inventory underestimates emissions from these devices (Allen et al. 2013, Allen et al. 2015). EPA should consider revising the current approach used for natural gas systems production sector pneumatic devices, which applies an emission factor to a single category of pneumatic devices to estimate potential emissions, then calculates net emissions by subtracting voluntary emission reductions based on Natural Gas STAR reports of industry replacement of high-bleed and intermittent-bleed devices with low-bleed or no-bleed devices. An alternative approach is to estimate net emissions from separate categories of pneumatic controller types and eliminate the application of voluntary reductions. Emission reductions resulting from the conversion of pneumatic controllers would be captured by changes in the activity factors of the different controller types. A three category division analogous to the Greenhouse Gas Reporting Program (low-bleed continuous, high-bleed continuous, intermittent-bleed) may be the most straightforward approach, but EPA should evaluate alternatives such as a two-category division (continuous, intermittent).

For petroleum systems production field operations pneumatic devices, EPA estimated net emissions for high-bleed and low-bleed devices in previous inventories. For the 2015 inventory, EPA is proposing to apply a fraction of the Natural Gas STAR reductions to petroleum systems pneumatics. An alternative approach is to update the activity factors by device type and not apply voluntary reductions. Aligning the petroleum systems pneumatic controller types with natural gas systems (low-bleed continuous/high-bleed continuous/intermittent or continuous/intermittent) is likely to simplify the methodologies.

Comment: There are two approaches that EPA could use to estimate pneumatic controller activity factors: 1) apply a ratio of pneumatic controllers per well to the Inventory well counts, or 2) extrapolate values from the GHGRP data for onshore petroleum & natural gas systems pneumatic controllers.

The first approach could use ratios reported by recent studies (2.7 controllers per well, Allen et al. 2015; 3.6 controllers per well, OIPA 2014), which would result in combined petroleum & natural gas systems activity factors of 3.5 – 4.6 million devices, about 3X – 4X higher than the corrected 2012 estimate in the 2015 inventory. Separate activity factors for natural gas and petroleum systems could be estimated using the proportion of gas and oil wells. It may be appropriate to apply distinct ratios of controllers per well to natural gas and petroleum systems if data sources indicate different average controller counts by well type.

The second approach using 2013 GHGRP data would result in an unadjusted activity factor of 412,000 devices for petroleum and natural gas systems. This value was estimated from 2013 reported emissions of pneumatic devices by assuming 78.8% methane and continuous operation; in future years, the device count will be directly reported by the operators. Since the GHGRP only includes data from facilities emitting ≥25,000 metric tons CO_2e per year, GHGRP activity factors need to be adjusted upward to account for non-reporting facilities. It has been estimated that GHGRP onshore production facilities represent approximately 85% of energy production. If the reported devices were scaled up by only 15% for non-reporters, the adjusted activity factor would be over 7X lower than the value estimated by the first approach, which suggests that this approach underestimates the number of devices. It may be more appropriate to scale up activity factors by the percentage of wells that report – this value could be estimated by comparing company- and county-level data from DI Desktop to the GHGRP data. If GHGRP data are used to estimate a national activity factor, it is critical that EPA verifies that the underlying device counts are accurate. GHGRP-based activity factors could be separated into natural gas and petroleum systems proportional to the GHG Inventory well counts by type.

Activity factors by controller type could be estimated by applying the GHGRP fractions of controllers by type to the national activity factors. There is higher confidence in 2013 GHGRP pneumatic controller data compared to 2011 and 2012 since these previous years were based on partial surveys. The 2013 data indicates that there are 28%, 5%, and 67% of low-bleed, high-bleed, and intermittent bleed devices, respectively. Natural Gas STAR data on pneumatic controller replacement since 1990 may be useful for estimating the fraction of controllers by type in previous years.

Comment: The inventory should use emission factors specific to pneumatic controller types such as low-bleed/high-bleed/intermittent-bleed. This would allow emission reductions from device replacement to be applied by updating activity factors instead of subtracting voluntary reductions. Recent data sources such as Allen et al. 2015, OIPA 2014, and Prasino 2013 may be useful for developing emission factors. These studies indicate a positively skewed distribution with a small fraction of devices contributing the majority of emissions. Allen et al. 2015 reports that many of these high emission devices are malfunctioning. This is readily observable for low-bleed devices measured in the study, which have a median emission rate of 0 scfh and an average emission rate of 10.4 scfh. This average emission rate, which is higher than the low-bleed regulatory definition of 6 scfh, is greatly affected by the 19% of devices exceeding 6 scfh.

One option to account for the skewed distribution of pneumatic device emissions is to use separate activity factors and emission factors for normally functioning and malfunctioning devices. Allen et al. 2015 provides useful data on the current emission rates and frequency of malfunctioning devices. Future changes in the frequency of malfunctioning devices may be estimated from leak detection and repair (LDAR) data from programs such as Natural Gas STAR. Alternatively, emissions could be reported separately for normally functioning pneumatic controllers and equipment leaks from pneumatic controllers. Emissions from normally functioning devices could be estimated using the complete activity factors and emission factors developed from data excluding malfunctioning devices. Potential equipment leak emissions from pneumatic controllers could be estimated using the frequency and emission rates of malfunctioning devices from Allen et al. 2015. These potential emissions could be scaled to other years proportional to the number of devices. To account for future emission reductions resulting from the repair of malfunctioning devices, voluntary reductions could be applied to pneumatic controller equipment leaks using data from Natural Gas STAR reports of pneumatic controller LDAR programs.

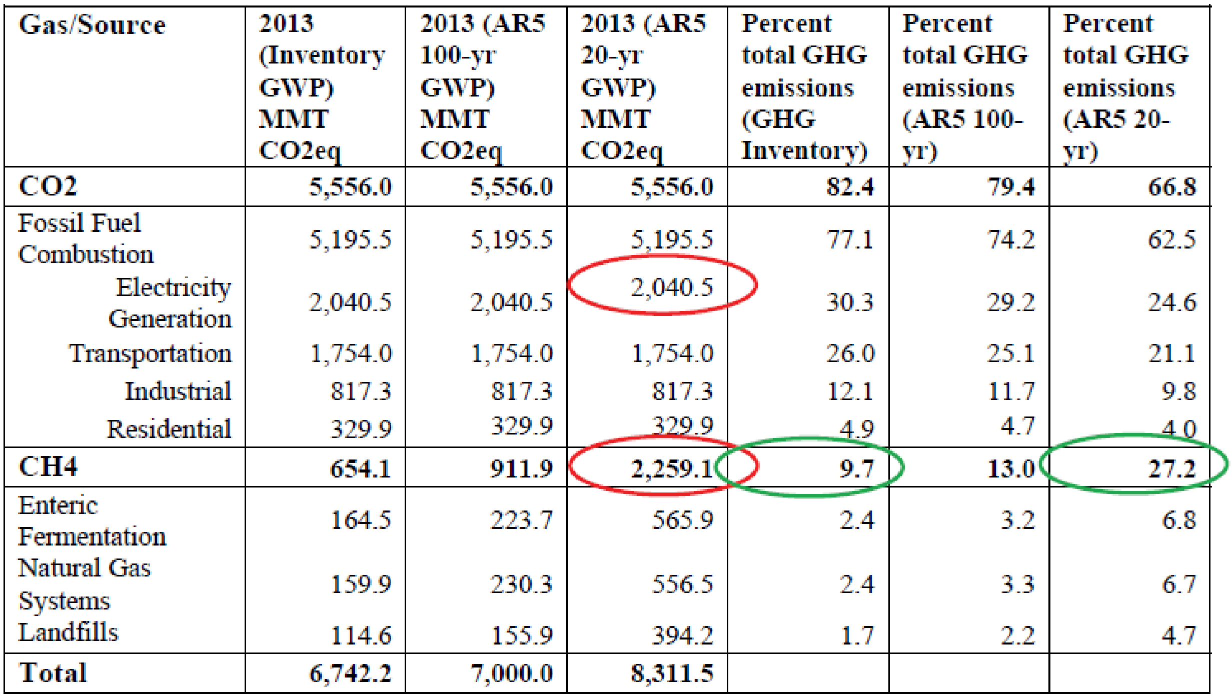
Commenter: Anna Moritz
Center for Biological Diversity (CBD)

Comment: One of the IPCC Fifth Assessment Report's ("AR5") breakthrough insights is the discovery of a fundamental flaw in previous calculations of GWP: the climate effect of CO_2 intrinsically includes carbon cycle feedbacks, but the GWPs of other greenhouse gases do not. Thus, to compare "apples to apples," it is necessary to include these feedbacks in the estimates of all greenhouse gas emissions. The Inventory, however, perpetuates the error by reporting only the lower, non-feedback 100-year GWP values for non-CO_2 gases. This omission causes serious inaccuracies in how the report presents and compares the respective greenhouse gases' climate change impacts.

We appreciate that EPA has included the AR5 100-year GWP values for all greenhouse gases in Annex 6.3 It is entirely unrealistic, however, to expect the wide range of Inventory readers to understand the significance of the Annex 6 information, much less to substitute their own calculations in lieu of those provided by EPA. The greenhouse gas inventory is relied upon by citizens, businesses, governmental agencies, and policy makers across the country, and they consult its prominently displayed information, especially its executive summary and tables. These do not display or explain the significance of the GWPs. As the examples discussed below and the attached exhibit vividly demonstrate, only actually running the numbers and displaying them in tables show their impact and avoid comparing apples to oranges. Thus, we strongly urge EPA to include climate-carbon feedbacks from all greenhouse gases and use the GWPs stated in AR5. To do otherwise is inaccurate and misleading.

Comment: Another glaring omission is the failure to compare, and in this case even to mention, greenhouse gas emissions based on their 20-year global warming potentials. The selection of a particular time horizon for GWPs influences the policy focus because the analysis and comparison occurs only at the selected time frame. Many policy analysts and decision makers, however, believe that a 100-year focus is important for long-term climate stabilization, while a near-term (20 years or less) focus is equally crucial because the next few decades will determine whether catastrophic and irreversible damage can be avoided before tipping points are crossed. Decision makers and the public should be presented with the 20-year effects of greenhouse gases to focus attention on short-term solutions that may abate immediate harm sufficiently to allow us to reach climate stability on a 100-year and beyond time scale.
The time-based distinction between GWPs is of key importance for a greenhouse gas such as methane. Methane is a short-lived greenhouse gas that remains in the atmosphere a little over a decade; by contrast, CO_2 has an atmospheric lifetime of a century and beyond. Methane has exerted the second largest warming influence since the Industrial Revolution, behind only CO_2. And crucially, the AR5 value for its 20-year GWP (86) is approximately 2.5 times higher than its 100-year GWP (34). The implications of this difference for responsive action are enormous, and reporting both GWPs for methane is therefore of key importance.

To illustrate these points, we reproduced Table ES-2 from the Inventory and presented both AR5 100-year and 20-year GWPs (with climate-carbon feedbacks) for all greenhouse gases. The results are striking. On a 20-year GWP basis, total U.S. methane emissions are approximately equivalent to the heating influence of CO_2 generated by the entire electricity generating sector. This is key information: EPA has embarked on a ground-breaking effort to create standards for power plants; since methane is an equivalent contributor to near-term climate change, EPA should place an equally high priority on methane mitigation strategies. Overall, on a 20-year basis, methane emissions constitute some 27% of total U.S. greenhouse gas emissions – instead of only about 10% as reported in Table ES-2. Put another way, reporting only an (incorrect) 100-year methane GWP results in a ratio between warming from methane and warming from CO_2 of about 1 to 10 (10%), while reporting the most accurate 20-year methane GWP shifts that ratio to 4 in 10 (40%). Presenting an accurate short-term comparison is thus critically important, and omission of these facts is highly misleading.



Gas/Source	2013 (Inventory GWP) MMT CO2eq	2013 (AR5 100-yr GWP) MMT CO2eq	2013 (AR5 20-yr GWP) MMT CO2eq	Percent total GHG emissions (GHG Inventory)	Percent total GHG emissions (AR5 100-yr)	Percent total GHG emissions (AR5 20-yr)
CO2	**5,556.0**	**5,556.0**	**5,556.0**	**82.4**	**79.4**	**66.8**
Fossil Fuel Combustion	5,195.5	5,195.5	5,195.5	77.1	74.2	62.5
Electricity Generation	2,040.5	2,040.5	2,040.5	30.3	29.2	24.6
Transportation	1,754.0	1,754.0	1,754.0	26.0	25.1	21.1
Industrial	817.3	817.3	817.3	12.1	11.7	9.8
Residential	329.9	329.9	329.9	4.9	4.7	4.0
CH4	**654.1**	**911.9**	**2,259.1**	**9.7**	**13.0**	**27.2**
Enteric Fermentation	164.5	223.7	565.9	2.4	3.2	6.8
Natural Gas Systems	159.9	230.3	556.5	2.4	3.3	6.7
Landfills	114.6	155.9	394.2	1.7	2.2	4.7
Total	**6,742.2**	**7,000.0**	**8,311.5**			

Excerpt from Appendix A. Entries for source categories are directly from Table ES-2 ("Recent Trends in U.S. Greenhouse Gas Emissions and Sinks") in the Draft GHG Inventory for 1990-2013 at ES-5. Data column 1 is a replicate of the last column in Table ES-2, which contains 2013 data. Data columns 2 and 3 in this table were compiled using IPCC AR5 100-year and 20-year GWPs. These GWPs include climate-carbon feedbacks, as recommended by the AR5. Methane GWPs: column 1 = 25; column 2 = 34 (biogenic) or 36 (fossil); column 3 = 86 (biogenic) or 87 (fossil). Data columns 4 through 6 reflect the percentage of total emissions (prior to removal of sinks) for each gas/source.

A compounding factor is that the methane emissions from certain sources are likely under-represented by EPA's analysis method. For instance, a number of peer-reviewed scientific studies suggest that methane leakage from natural gas systems could be as much as double what EPA assumes. Likewise, methane leakage from landfills is notoriously difficult to monitor and may also be much larger than EPA's calculations assume. In sum, not only does the Inventory fail to include critical information about methane's influence over the next 20 years, but even the corrected values we calculate here likely are a considerable under-estimate of methane emissions.

Comment: We commend EPA for using IPCC Fourth Assessment Report ("AR4") GWP values for the first time in this Inventory, a vast improvement over the use of Second Assessment Report values. While this is an important step, we and other organizations previously asked EPA to utilize the most up-to-date science and adopt the most recent methane GWPs from AR5, and to report both 100-year and 20-year methane GWPs. EPA declined to do so because current international reporting requirements under the United Nations Framework Convention on Climate Change employ only 100-year GWPs, and will begin using AR4 GWPs in 2015.

While we understand EPA’s need to comply with international reporting requirements, we renew our call on EPA to update the emissions reported in the U.S. GHG Inventory to also reflect the AR5 GWPs, as well as report normalized emissions using both 20-year and 100-year GWPs for methane. The U.S. GHG Inventory is seminal, foundational document domestically for both government and private-sector decision-making and analysis. Providing reliable data for domestic use is one of its key purposes, separate and apart from international commitments, and requires the most accurate quantification of climate impacts possible. While the inclusion of Appendix 6 in the Inventory is helpful to the most careful readers – those who then also take the next step and perform their own calculations as we have done here – we request that EPA include these calculations to make the information both prominent and easily accessible.

Commenter: Cynthia Finley

National Association of Clean Water Agencies (NACWA)

Comment: The emissions from POTWs in the 2013 Inventory are essentially the same as those in the 2012 Inventory. NACWA appreciates the clarifications that have been made over the past few years to clarify the emissions calculations and the factors that are used. NACWA’s primary concern with the Inventory is the extensive use of potentially outdated data and extrapolated data in the emissions calculations. For example, the 1992, 1996, 2000, and 2004 Clean Watershed Needs Surveys (CWNS) are used as the basis for the percent of wastewater flow to aerobic and anaerobic systems, the percent of utilities that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters. EPA states that since the 2008 CWNS does not contain information that is detailed enough for use in the Inventory, information for the years 2004 through 2013 was forecast from the rest of the time series. The 2004 CWNS is likely outdated now, and forecasts made from it and the previous surveys may not accurately reflect recent trends and practices for wastewater utilities. A similar forecast was made for sludge generation and protein consumption.

Comment: NACWA’s other concern with the Inventory calculations is the lack of specific emissions factors and calculation methods for the U.S. As NACWA has explained in comments on the Inventory in previous years, the Association believes that the nitrogen loading rates for N2OEFFLUENT are sourced incorrectly and that using information from the existing National Pollution Discharge Elimination System (NPDES) database will yield more accurate and justifiable loading rates. The NPDES permitting program represents long-term, nationwide facility performance that would allow emissions estimate projections over the time series represented in the Inventory. If EPA decides not to investigate its own databases, the average nitrogen loading rate of 15.1 g N/capita-day from Metcalf and Eddy (2003) represents the industry standard and is supported by a wealth of data widely confirmed in U.S. practice. This value represents all domestic sources of nitrogen, the use of other nitrogen-containing compounds, and both residential and commercial sources. EPA uses other values from Metcalf and Eddy (2003), such as the BOD5 production rate and BOD5 removed by primary treatment. Since this reference is valid for other factors, it should also be valid for the nitrogen loading rate.

Comment: NACWA agrees with EPA’s planned improvements and encourages EPA to investigate additional data sources as soon as possible to ensure the accuracy of future Inventories.

Commenter: Brad Upton

National Council for Air and Stream Improvement, Inc. (NCASI)

Comment: Production statistics for the pulp and paper sector are too high. Table 7-12 lists 2013 production of the pulp and paper sector at 131.5 million metric tons, based on data from the Food and Agriculture Organization of the United Nations (FAO), and includes a note that this figure represents the sum of woodpulp production plus paper and paperboard production. Summing woodpulp, paper, and paperboard production results in double counting, because the majority of woodpulp production is used to produce paper and paperboard at integrated mills (an integrated mill includes both pulping and papermaking at the same facility, with a single wastewater treatment system).

A more appropriate method for characterizing total pulp and paper sector production would be to sum paper production, paperboard production, and market pulp1 production. For 2013, the American Forest and Paper Association (AF&PA) reported total production of paper and paperboard to be approximately 73 million metric tons and total production of market woodpulp to be approximately 8 million metric tons2. Based on these statistics, total pulp and paper sector production in 2013 was approximately 81 million metric tons. AF&PA provides its Statistical Summary reports to the Library of Congress annually, and has indicated a willingness to provide a gratis copy of the report directly to EPA. The August 2014 issue of the Statistical Summary is attached for your convenience (information on production of paper and paperboard can be found in Table 1 and information on production of market wood pulp can be found in Table 15).

Comment: EPA characterizes wastewater generation per ton of production based on water discharge statistics from AF&PA Sustainability Reports. These are the most current and relevant data for this characterization, and NCASI submits no comments on this use other than to emphasize that the agency should ensure it is using the most current version of the AF&PA Sustainability Report, which is published biennially, and attached for your convenience.

Comment: EPA characterizes the organic load in untreated wastewater using a legacy value of 0.4 gram BOD per liter of untreated effluent and a multiplier of 2 to convert from BOD to COD. NCASI has very limited data on untreated effluent organic load. Therefore, until additional data are available, we cannot suggest an alternative value.

Commenter: Erica Bowman

America’s Natural Gas Alliance (ANGA)

Comment: For the past several years, ANGA has submitted comments on EPA’s Draft GHG Inventories. In recent GHG Inventories, EPA has addressed some of these concerns, including adjusting the methodologies for estimating the frequency of well re-fracturing, emissions from hydraulically fractured well completions and workovers, and emissions from liquids unloading. ANGA supported these changes, which more accurately accounted for actual field practices. We encourage EPA to continue upgrading the GHG Inventory with net emission factors in place of potential emission factors as more data become available. We believe more accurate data will show lower methane emissions from the natural gas sector.

Comment: In the 2014 GHG Inventory, EPA adjusted the methodology for completions and workovers with hydraulic fracturing. These adjustments established four technology specific emissions factors for wells with hydraulically fractured completions and workovers using data from the 2011 and 2012 Greenhouse Gas Reporting Program (GHGRP) Subpart W.

In the 2015 Draft GHG Inventory, these emissions factors are updated using additional data from the 2013 GHGRP. These updates result in reductions for the emissions factors for three of the four well categories. Additionally, the updated data show more wells using RECs and fewer wells that directly vent all flowback emissions in 2012 compared to the 2014 GHG Inventory. These activity data better reflect actual industry practices, including the voluntary use of RECs by many producers. ANGA supports these changes, which address inaccuracies found in previous GHG Inventories that we have commented on in the past. We would also support further sub-categorization to recognize the differences between hydraulically fractured completions and hydraulically fractured workovers.

Comment: While ANGA supports the new emission factors for uncontrolled well completions as more accurately representing actual industry practices, they remain higher than measured results from the recent study by researchers at the University of Texas-Austin and supported by Environmental Defense Fund (UT Austin/EDF study). At 36.8 metric tons (MT) methane per vented well completion, for example, the estimate in the Draft 2015 GHG Inventory is one order of magnitude higher than similarly configured completions in the UT Austin/EDF Study, which found a range of 0.5-4 MT methane per completion event for those wells vented directly to atmosphere. Much of this difference can be attributed to the choke flow calculation methodology option in the GHGRP. The choke flow calculation methodology was not designed for use in multi-phase flow applications, and as such can often deliver erroneous results when compared to direct measurement. While ANGA supports continued use of the GHGRP data to update emission factors, ANGA encourages EPA to remove outlier data from the emission factor calculation and use only measured data in the GHGRP for the calculation of emission factors, not data derived from the choke flow equation methodology.

Comment: As noted above, ANGA supports the use of GHGRP data to establish emission factors and encourages EPA to continue using this data source to refine the emission factors for hydraulically fractured well completions and workovers. As industry technology and practices improve to further reduce methane reductions and the GHGRP continues to update its calculation and reporting methodologies, the emission factors for hydraulically fractured wells and completions should be adjusted accordingly. In addition to improving the accuracy of the GHG Inventory, creating emissions factors that more closely match the GHGRP data will provide public confidence in and increase uniformity across EPA’s data programs.

Comment: While ANGA continues to believe that EPA’s estimate of the number of uncontrolled well completions and workovers is too high, we understand that this number will decrease significantly in future GHG Inventories because they will factor in requirements included in the 2012 Oil and Gas NSPS. This rule requires the use of RECs for almost all completions and workovers after January 1, 2015 and required flowback emissions to be routed to a completion combustion device starting in October 2012. The impact of this rule can clearly be seen in the Draft 2015 GHG Inventory, which reports methane emissions from these activities decreasing by nearly 52 tons from 2012 to 2013.

Comment: In response to EPA’s request for feedback on possible changes to the methodologies for estimating emissions from pneumatic controllers and liquids unloading, ANGA supports the use of direct measurements to develop technology- and/or process/function-specific emissions factors. Additionally, ANGA supports the development of emissions factors and activity data on a regional as opposed to national basis. We believe that aggregation of regional data to calculate national emissions provides a more accurate estimate that accounts for regional variation in gas composition, production practices, and regulation.

Comment: Given the magnitude of the changes that the Agency has made over the past five years both increasing and decreasing estimated emissions from natural gas production, the underlying data and assumptions must be rigorous and well supported. ANGA appreciates the changes EPA has made to its methodology for estimating emissions from liquids unloading, its estimate of the frequency of workovers, and its methodology for hydraulically fractured well completions and workovers. We encourage EPA to continue updating its methodology and emissions factors with technology specific and region specific emissions factors based on valid data, assumptions and calculations. However, given the underlying uncertainties of the current data, ANGA does not support the use of the emissions estimates presented in the GHG Inventory as the basis for any analysis or regulatory action.

Commenter: Karin Ritter

American Petroleum Institute (API)

Comment: Regarding EPA's approach for designating "associated gas wells" within the category of "oil wells", EPA may be over estimating the number of associated gas wells and is not consistent with EIA and state approaches. API urges EPA to make note of this in the final inventory and commit to re-evaluate this as part of the methodology improvements for the next GHGI cycle.

Comment: API advises EPA to carefully analyze and screen GHGRP reported data in order to improve the validity of data used in the 2013 national GHGI. Obvious data outliers should be excluded or otherwise corrected to prevent disproportionately impacting the derivation of emission factors (EFs) or extrapolation of information for the national 2013 GHGI, as may be evident from the changes made to 2012 GHGRP data due to corrections of industry data. As discussed previously with EPA, the GHGRP data may potentially include incomplete or incorrect data due to ambiguity in implementation of approved EPA procedures, errors in applying the GHGRP calculations, and faults in data aggregation and reporting.

Comment: API supports the use of information reported through the GHGRP for developing the GHG emissions estimates for the refining sector in the 2013 national GHGI. Although the GHG emission profile for refineries has changed over the years due to additional controls, the use of throughput to scale emissions for 1990-2009 is an acceptable surrogate.

Comment: As API commented previously during the Expert Review Version of the 2013 GHGI, some reporters voluntarily reported emissions data for oil well completions and workovers with hydraulic fracturing in their 2011 through 2013 GHGRP data. API sorted the GHGRP data to examine those data sets reporting emissions data for oil formations where either Equation 10-B or 10-A with measured emissions were used. This excludes data sets which relied on the choke flow equation to estimate emissions. As a result of this analysis, API identified 149 reported data sets providing emissions data for 1,675 completions and 226 workovers for the years 2011 through 2013 combined. This is a substantial amount of information. Even with some ambiguities in the reported data, there is sufficient information to develop updated emission factors rather than using decade's old data from the 1996 GRI/EPA study.

API recommends the use of two data categories, which maximizes the use of data available from the GHGRP. Table 1 summarizes the resulting emission factors for these two data categories: vented oil well completions and workovers without REC, and all other oil well completions and workovers (Flared w/o REC, Vented w/REC, or Flared w/REC). Although there appear to be some data outliers, in general the emission data currently available shows that vented workovers and completions without REC have a distinctly higher emission rate than completions and workovers flared without REC, flared with REC, and vented with REC.

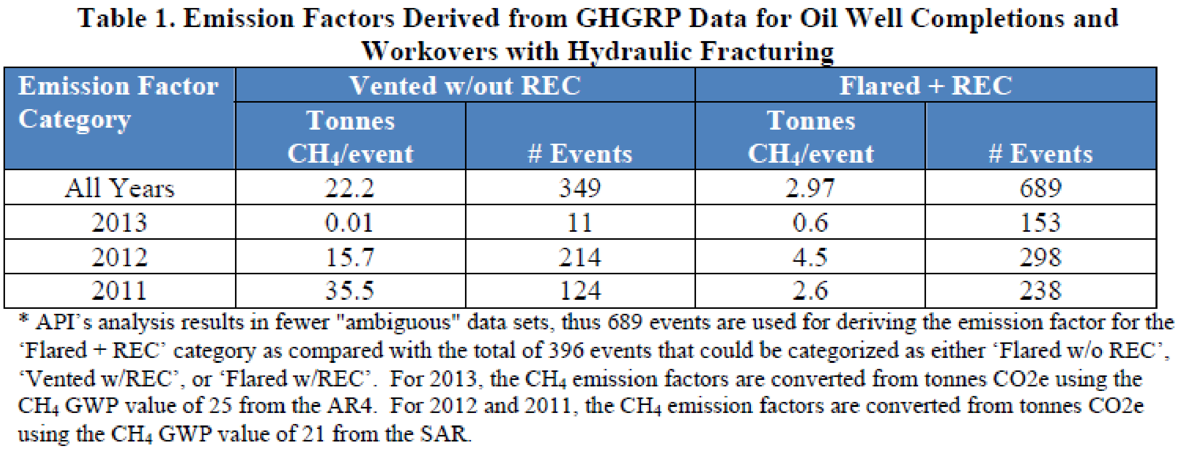


Table 1. Emission Factors Derived from GHGRP Data for Oil Well Completions and Workovers with Hydraulic Fracturing

Emission Factor Category	Vented w/out REC		Flared + REC	
	Tonnes CH_4/event	# Events	Tonnes CH_4/event	# Events
All Years	22.2	349	2.97	689
2013	0.01	11	0.6	153
2012	15.7	214	4.5	298
2011	35.5	124	2.6	238

* API's analysis results in fewer "ambiguous" data sets, thus 689 events are used for deriving the emission factor for the 'Flared + REC' category as compared with the total of 396 events that could be categorized as either 'Flared w/o REC', 'Vented w/REC', or 'Flared w/REC'. For 2013, the CH_4 emission factors are converted from tonnes CO2e using the CH_4 GWP value of 25 from the AR4. For 2012 and 2011, the CH_4 emission factors are converted from tonnes CO2e using the CH_4 GWP value of 21 from the SAR.

Until regular reporting of oil well completions and workovers is established, API recommends developing the emission factors based on all three years of available GHGRP data combined. The factors should be re-evaluated when more information is available.

Comment: API agrees with excluding 2000 GOADS data.

Comment: API agrees with the proposed approach for applying GOADS data to previous years. API recognizes that using the 2005 GOADs data for inventory years 1990 through 2006 is a bit of a stretch for the early inventory years, but believes this is the best option of those considered.

Comment: The proposed method of obtaining platform counts will absolutely result in overestimated emissions, as the platform census is not able to differentiate between active and nonactive platforms. There is an industry-wide tool called "Lexco/OWL" that should have better information. BOEM/BSEE is certainly aware of this tool because they maintain the data in the tool. It would be informative to understand whether EPA plans to count each structure as a "platform", or each complex. BOEM designates bridge connected structures as a "complex" with a unique complex ID. While the method of determining an average emission factor and applying it to facilities according to the 4 facility "buckets" seems like it would result in an overestimation of emissions, applying the factor to each structure, rather than each complex will certainly result in flawed, overestimated emissions.

Comment: Is this volume of gas received from MMS/BOEMRE a single volume that a percentage is then called flared? If so, the method looks to be a very inaccurate method to split out the combusted from the uncombusted emissions. A method to potentially get closer to combusted vs uncombusted emissions

would be to start with the gas release volumes that PRA gas volume accounting has provided to BOME on the OGOR reports over the years. Even if BOME has retained this data, determining what portion of each of these reported volumes is combusted, or not, would be a labor-intensive exercise. It may be easier to ID the platforms that have a true flare system that combusts the gas and apply these volumes.
The above effort would be needed because prior to 2010, PRA volume accounting provided volumes of gas released from fields to BOME as "flare." Re-write of Subpart K in 2010 moved the offshore producers to update their OGOR reports to reflect separate reporting into a flare or a vent release.

Comment: API provided an analysis of the GHGRP data to EPA in October 2014 and in our comments on the Expert Review version in the GHGI. Table 2 compares emissions factors that API developed from the 2013 GHGRP data, those proposed by EPA for the 2013 national GHGI (which are based on a combination of 2011-2013 data) as well as combined 2012-2013 data that are proposed by API for the 2013 national GHGI.

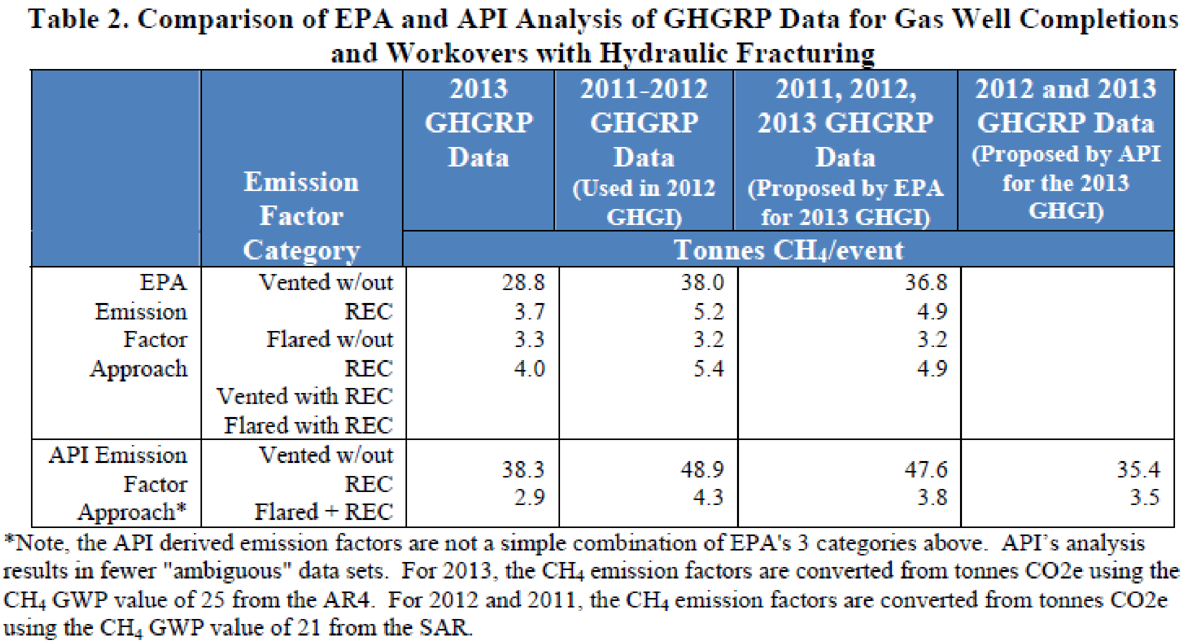


Table 2. Comparison of EPA and API Analysis of GHGRP Data for Gas Well Completions and Workovers with Hydraulic Fracturing

	Emission Factor Category	2013 GHGRP Data	2011-2012 GHGRP Data (Used in 2012 GHGI)	2011, 2012, 2013 GHGRP Data (Proposed by EPA for 2013 GHGI)	2012 and 2013 GHGRP Data (Proposed by API for the 2013 GHGI)
		Tonnes CH$_4$/event			
EPA Emission Factor Approach	Vented w/out REC	28.8	38.0	36.8	
	Flared w/out REC	3.7	5.2	4.9	
	Vented with REC	3.3	3.2	3.2	
	Flared with REC	4.0	5.4	4.9	
API Emission Factor Approach*	Vented w/out REC	38.3	48.9	47.6	35.4
	Flared + REC	2.9	4.3	3.8	3.5

*Note, the API derived emission factors are not a simple combination of EPA's 3 categories above. API's analysis results in fewer "ambiguous" data sets. For 2013, the CH$_4$ emission factors are converted from tonnes CO2e using the CH$_4$ GWP value of 25 from the AR4. For 2012 and 2011, the CH$_4$ emission factors are converted from tonnes CO2e using the CH$_4$ GWP value of 21 from the SAR.

As Table 2 shows, the emission factors for workovers and completions flared without REC, flared with REC, and vented with REC are essentially the same within the expected uncertainty bounds.

Over time, the majority of completions and workovers will utilize REC due to regulatory requirements and increased use of control technologies such as gas separation and capture with, or without, flaring. API continues to contend that these three categories can be combined resulting in only two categories for grouping the completion and workover emissions data for deriving representative emission factors. These two categories will be more straightforward to back cast for previous reporting years in the national GHGI and are consistent with current practices and the phased-in implementation of emission control regulations.

EPA's memo on the proposed revisions to hydraulically fractured gas well completions and workovers does not indicate any assumptions EPA used in evaluating the GHGRP data for the 2013 national GHGI.

Differences between API's analysis and EPA's are apparent in the comparison of emission factors for vented completions and workovers without REC, indicating different assumptions in the analysis. EPA should document any assumptions used in the approach.

Finally, due to potential data issues associated with the first year of reporting, API suggests excluding 2011 data in the development of emission factors. The GHGRP provides sufficient data to support annual updates to the emission factors for years going forward, as indicated by the API proposed emission factors that are based on the GHGRP data from 2012-2013 only.

Comment: API's analysis of the GHGRP data shown in Table 2 is based on information from 4,843 of the total 27,207 completion and workover events reported for 2013. Additional information will be reported through the GHGRP in 2015 as companies report previously deferred data. The deferred data should provide additional clarity and improve the ability to classify the completions and workovers emissions. API also believes that the quality of emission data reported to the GHGRP has improved over time. Therefore, API suggests that EPA examine data that would be reported through the GHGRP by the end of March 2015 and consider its applicability for potential development of regional emission factors and activity data that could be used starting with the 2014 national GHGI.

Comment: API appreciates EPA's effort to improve transparency and reproducibility in the way it generates the natural gas and petroleum system well counts. As EPA has proposed in the 2013 national GHGI, API believes the approach to classifying all active production wells as either "Non-associated Gas Wells" or "Oil Wells," then defining an oil well sub-population as "Associated Gas Wells," all based solely on GOR would simplify the well count process and improve reproducibility. API also believes this approach would be the best option to implement since this option clarifies the well count process while still allowing for a distinction between associated and non-associated gas wells. In the expert review version of the inventory, API had commented that if this approach is adopted, EPA should use a GOR ratio of >100 Mcf/bbl to define a "gas well" versus an "oil well" and then use the GOR > 6 Mcf/bbl threshold to define an "associated gas well" as a subset of "oil wells" to best reflect the wide range of definitions used by the states.

EPA had stated that they would "apply a GOR threshold to identify a sub-population of 'Oil Wells' that produce substantial amounts of gas and should be classified as 'Associated Gas'." However, in the Public Comment version of the 2013 GHGI, EPA essentially chose a GOR of zero for the threshold by deciding that "any well within the oil wells population . . . that also produces any gas is classified as an associated gas well in the Inventory" (emphasis added). This means that any well with a GOR of 100 MCF/Bbl or less (the threshold for an oil well) that also has any gas production, will be categorized as an associated gas well.

API believes that this choice is incorrect. It is very common for wells that produce mainly oil to also produce a small amount of gas (as demonstrated in the query into the Drilling Info database as shown in Table 3 below). The difference between the previously proposed Options (as described in the Expert Review version of the 2013 GHGI) is that the preferred approach meant "to treat oil wells with significant gas production differently than primarily gas-producing or oil-producing wells (as they are expected to have emissions somewhere between the two populations)—and therefore included a population of 'associated gas' wells." By not including a meaningful threshold to distinguish the sub-population of associated gas wells from oil wells, the way EPA has elected to implement this approach fails to treat these wells differently.

As EPA notes, “The GOR selected to define the “Associated Gas Wells” population will need to be thoughtfully chosen and well-documented.” API recommends using a threshold of 6 MCF/Bbl to separate out the subpopulation of “associated gas wells” from the selection of oil wells. This is the threshold that the EIA uses to classify associated gas wells versus oil wells. Table 3 below exhibits the difference in well counts when using a threshold of 6 MCF/Bbl versus a threshold of any gas production. The example is based on a sample of 2014 wells in the Eagle Ford and Williston basins using the Drilling Info database. In each case, “Gas Wells” and “Oil Wells” are distinguished by the 100 MCF/Bbl threshold described by EPA. The example emphasizes that using the EPA’s definition for “associated gas wells” would classify virtually all “oil wells” as “associated gas wells” in the Williston and Eagle Ford Basins.

Table 3. Comparison of Well Counts for Williston ad Eagle Ford Basins

Threshold for Associated Gas Wells	*Gas Wells*	*Oil Wells*	Associated Gas Wells (Sub-population)	Strictly Oil Wells (Sub-population)
Williston Basin				
Any Gas Production (EPA)	*2,844*	*13,499*	13,498	1
6 MCF/Bbl	*2,844*	*13,499*	280	13,219
Eagle Ford Basin				
Any Gas Production (EPA)	*606*	*11,893*	11,734	159
6 MCF/Bbl	*606*	*11,893*	3,175	8,718

Despite the obvious bias introduced by EPA’s implementation of the selected approach, API recognizes that EPA might not be in a position to make major changes to the GHGI prior to submitting it to the UNFCCC by mid-April 2015. Nonetheless, API is urging EPA to note in the final report for the 1990-2013 GHGI that their assignment of “associated gas wells” within the “oil wells” category may be challenging and may lead to over counting “associated gas well”, and is not compatible with EIA’s and States’ approaches as well as industry’s recommendations. EPA should go further and commit itself to address this issue more fully as part of methodology improvements for the next GHGI cycle.

Comment: It should also be noted that in EPA’s supplemental note on pneumatic controllers the discussion on controller counts per well refers to only some 400,000 wells nationwide, which is less than half the wells in the U.S. API expects that with the updated pneumatic device inventories that would become available with 2014 data, it will be possible to improve both the counts of pneumatic devices per well.

Comment: Emissions from condensate tanks in natural gas production operations have increased 13% from 2012 due to large increases in the activity data. The memo on Proposed Revisions to Well Counts Data indicates that condensate production data are taken from EIA. Such a large increase in the activity data warrants an explanation in the 2013 national Inventory.

Comment: There is a discrepancy in the emissions data reported for gas well completions and workovers with hydraulic fracturing in the Rocky Mountain region. Table A-133 (page A-189) reports 604,275 workovers per year for this one region. This appears to be a typo.

Commenter: Lesley Fleischman and David McCabe

Clean Air Task Force (CATF)

Comment: We are pleased to see that EPA is working to improve the GHG Inventory on multiple fronts and is using new data sets as they become available. We also endorse efforts to make the methodology of Petroleum and Natural Gas Systems sections of the inventory more transparent.

Comment: Based on our review of the Pneumatics Memo and Appendix 3 of the Public Draft, CATF agrees that the Inventory should apportion emissions reductions reported to Natural Gas STAR for pneumatic controllers between the Natural Gas and Petroleum Systems sections of the Inventory.

However, the overall approach EPA takes to pneumatic controllers produces inventory documents which are very opaque. EPA should use a similar approach as used for well completions to tabulate emissions from pneumatic controllers. Instead of listing potential emissions and regulatory and voluntary reductions for pneumatic controllers, EPA should list net emissions for multiple classes of pneumatic controllers, such as high-continuous bleed, low-continuous bleed, intermittent bleed, and zero-bleed. The final category has no emissions, but should be tracked in the inventory to provide fuller information about activity levels. This approach would closely parallel the approach used for gas well completion emissions.

Voluntary and regulatory emissions reductions from pneumatic controllers are quite substantial and EPA may wish to tabulate the magnitude of those reductions in the inventory. This is easily handled with a separate table.

This would be far better than handling the various classes of controller by calculating the average emissions per controller, as the inventory currently does. This would make the inventory easier to understand, make it easier to compare inventory emissions factors to measurements in the field, and make the implications of potential future policies clearer. Finally, it would allow much more straightforward comparison with the GHGRP and would make it more straightforward to tabulate the effects of NSPS Subpart OOOO on emissions.

Comment: The Pneumatics Memo also highlights several studies that indicate that the number of pneumatic controllers per well is higher than previous estimates. The Allen et al. 2014 study suggests that there are at least 1.5 controllers per well, and the Oklahoma Independent Petroleum Association study suggests that there is an average of at least 3.6 controllers per well (and an even more for newer wells). The current inventory estimates approximately 1 pneumatic controller per well, which is clearly too low in light of these studies. Thus, we suggest that EPA increase its assumption about the number of pneumatics per well based on these recent studies.

Comment: In Table 6 of the Pneumatics Memo, EPA notes that the OIPA study reports emissions factors of: “Average 1.05 scf whole, gas/hour; 0.40 scf/h intermittent vent, 21.54 scf/h continuous bleed.” However, the emissions factors quoted in the OIPA study represent manufacturer reported emissions rates, and thus they do not measured emissions rates. Studies like Allen et al. 2014 have found that measured emissions are much higher than manufacturer reported emissions. Thus, we caution the EPA against using emissions estimates from the OIPA study and recommend that EPA uses, or at least considers, direct measurements in revising the emissions factors.

Table 6 also presents results from the Prasino Study. It notes that the report lists emissions factors of 9.2 scfh and 9.0 scfh for “high-bleed controllers.” It is critical to note that the Prasino study considered any controller actually emitting over 6 scfh to be a "high-bleed" controller, even though many of the controllers that they classified as such were designed to emit less than 6 scfh. Excess emissions from these controllers, which are generally classified as low-bleed controllers (because that's what they are designed to be, and in general well operators are not checking actual bleed rates from installed controllers), are a significant concern. However, emissions from controllers designed to emit more than 6 scfh are probably considerably larger than emission from malfunctioning low-bleeds. Averaging in a large number of malfunctioning low-bleeds into this data set leads to an average emissions factor which is far lower than the expected emissions from controllers designed to be high-bleed. As a result, this emissions factor is not comparable with other emissions factors for high-bleed pneumatic controllers.

Comment: We were pleased to see that the EPA is starting to think about including emissions from abandoned wells in the GHG Inventory. This is an area with a great deal of uncertainty, both in terms of the number of abandoned wells and the emissions from those wells. However, this could be a significant emissions source and it could help fill the gap between bottom up and top down studies of methane emissions. We encourage the EPA to review the Kang et al. study, published in December 2014 ("Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania").

Comment: EPA stated that it is seeking comments on the casinghead gas emissions source. The GHG Reporting Program has data on casinghead gas emissions in the source category: Associated Gas Venting Flaring. In 2013, companies reported methane emissions in this category of 84,103 metric tons. In contrast, in the draft GHG Inventory, emissions from Stripper wells were 14,215 metric tons in 2013. Thus, it is clear that the GHG Inventory underestimates casinghead gas emissions. One reason for this discrepancy is the fact that casinghead gas emissions occur at a wider set of associated gas oil wells, not only at stripper wells. Thus, it may be appropriate for the EPA to peg casinghead gas emissions to the new category of Associated Gas Oil Wells, rather than the Stripper Well category.

Commenter: Theresa Pugh

Interstate Natural Gas Association of America (INGAA)

Comment: The T&S methane emissions inventory in the Draft GHG Report "increases" from 51.8 million metric tons CO_2 equivalent (CO_2e) in 2012 to 54.4 million metric tons CO_2 equivalent (CO_2e) in 2013. Some portion of this increase can be attributed to the EPA's decision to increase the global warming potential of methane from 21 to 25. EPA should clarify the extent and impact of the changes to the methane global warming potential on the National Inventory, including T&S methane emissions.

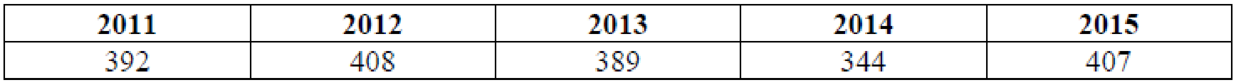
Comment: It also appears that the methodology used by EPA to calculate GHG emissions from the T&S sector is a significant contributor to the year-over-year increase in emissions attributed to this sector. EPA has not changed the emission factors (EFs) used for the T&S sector other than when EFs were updated to reflect centrifugal compressors with wet seals. Nearly all other EFs from T&S are from the 1996 EPA-GRI Report and have not changed since the National Inventory reporting started in the late 1990s.

Changes in Activity Data (e.g., compressor counts, facility counts) from year-to-year often are driven by methodology rather than real changes in physical assets. Thus, nominal year-to-year changes in "emissions" for T&S operations in the Draft GHG Report often are driven by methodology rather than actual emissions.

As a result of this and other marginal year-to-year changes for other natural gas sectors, some have reported that methane emissions from natural gas operations increased by 1.5 percent from 2012 to 2013. This increase is likely a calculation methodology change rather than an actual change in emissions.

The Draft Annex Report indicates that the T&S methane emission increases from 2012 to 2013 are driven by changes to the estimated number of storage station facilities and the related change in compressor counts at storage facilities (i.e., compressor counts are based on the storage facility counts because an average number of compressors per facility is assumed). According to footnote 2 in Table A-137 of the Draft Annex Report, EPA adjusts the storage facility count from year-to-year based on "ratios for relating other factors for which activity data are available." However, the related process or operational parameter used for this scaling is not apparent. Therefore, INGAA recommends that EPA provide greater transparency to explain the methodologies and assumptions embedded into its National Inventory.
This methodology has resulted in the following changes in storage station facility counts for the 2011 report through the 2015 Draft GHG Report.

Table 1. Annual Variants of Storage Facility Data Based Upon Prior Inventories



2011	2012	2013	2014	2015
392	408	389	344	407

Similar relative year-to-year changes occur for reciprocating and centrifugal compressors at storage facilities. Clearly, this is not indicative of actual year-to-year changes in the number of facilities and compressors that are in operation. While there may be some year-to-year changes in the number of facilities in actual operation, the discrepancies appear to go far beyond this. It should be incumbent upon EPA to differentiate between changes in emissions attributable to actual changes in facilities versus changes attributable to the methodology.

Regardless of the basis of the scaling adjustment, it is not apparent that this scaling provides a comparable real-world change in methane emissions, especially since EFs are based on older studies and have not been updated to consider Subpart W data. There also are assumptions in the National Inventory about reductions in emissions based on Gas STAR Gold information that introduce some fluctuations (and uncertainty). INGAA urges EPA to highlight and explain how these factors affect calculation of the National Inventory each year.

The Draft GHG Report should be revised to describe clearly the calculation methodology and to clarify the uncertainty in estimates and limitations in the data reflecting a year-to-year increase (or decrease). Failure to clarify these calculation methodology changes can result in faulty and inaccurate conclusions regarding total national GHG emissions and emissions from industry sectors. An accurate National Inventory is essential for stakeholder understanding of emissions from the industrial sectors and for future policy decisions.

Comment: U.S. domestic natural gas is a key component of the U.S. energy portfolio. Because of the fuel's importance and the sharp increase in domestic supply over the past decade, interest in GHG emissions—especially methane emissions from natural gas systems including T&S operations—is keen. For many natural gas system emissions sources, including most T&S sector sources, the national estimates are based on EFs from the EPA-GRI project that resulted in the 1996 EPA-GRI Report. Most of the EFs used for the T&S sector have not changed since the 1996 EPA-GRI report. Although EPA updated EFs associated with centrifugal compressors with wet seals, nearly all other EFs from the T&S sector are from the 1996 EPA-GRI Report and have not changed since National Inventory reporting started in the late 1990s. Further, the fact that EPA has not differentiated changes in components (such as through new technology or new measurements) may further compound the inaccuracies in the National Inventory calculations.

With significant new emissions data becoming available from the mandatory Greenhouse Gas Reporting Program (GHGRP) and other stakeholder projects, and new technological advances, it is imperative that EPA undertake efforts to analyze the new studies, reassess and update historical emissions data, and integrate improved emission estimates into the National Inventory.

INGAA recognizes that EPA has revised production-related methane emission estimates in recent annual reports. The agency has made an effort in the past three years to review, compare and incorporate GHGRP Subpart W data for the production sector. INGAA supports EPA initiating a similar process to review methane emission estimates in the T&S sector.

Comment: Significant differences between the GHGRP Subpart W estimate and Draft GHG Report estimate of methane emissions for the T&S sector suggest that the Draft GHG Report data may be over-stated. The Subpart W methane emissions estimates are about an order of magnitude lower than the Draft GHG Report estimate. This is due in part to the GHGRP reporting threshold that results in less than a third of compressor stations reporting. However, if GHGRP Subpart W estimates are normalized and scaled using the activity data for T&S estimates in the Draft GHG Report (i.e., based on activity data of facility count and compressor count), estimates based on Subpart W data are still significantly lower than the estimate in the current Draft GHG Report.

As the EPA is aware, the T&S sector (along with the gas processing sector) are unique within the GHGRP, in that direct measurement is required for several key sources, such as emissions from reciprocating compressor rod packing and leakage associated with compressor unit isolation valves and compressor blowdown valves. Thus, thousands of measurements have been completed at T&S facilities since Subpart W reporting began in 2011. The GHGRP data is intended to be used as a basis for the National Inventory and related policy decisions regarding GHG and methane emissions, but the EPA's Subpart W data for T&S operations are currently not being used for that purpose. INGAA urges the EPA to integrate Subpart W data into the National Inventory.

Comment: The Draft GHG Report includes a "Planned Improvements" section that mentions the availability of additional data from the GHGRP and other sources. It is imperative that the EPA implement a plan to incorporate the GHGRP data for T&S sources into the existing 1990-2014 National Inventory estimate as well as future estimates. INGAA offers its support for an effort to compile and analyze this data to improve EFs from key sources such as compressors, and use updated EFs to improve the National Inventory.

Comment: T&S facilities are required to measure many sources (e.g., compressor related vent lines) and measurement data are available from GHGRP Subpart W reports submitted for the 2011-2013 annual reporting years. The measurements for 2014, along with additional data from 2011-2013 related to EPA's confidentiality determinations that must be reported this year, will be reported by March 31, 2015. This data also should be integrated into the National Inventory.

Comment: Moreover, as the EPA is aware, natural gas systems operators, including INGAA members, are also conducting a collaborative methane emissions project with the Environmental Defense Fund. A Colorado State University paper on T&S measurements was recently published.5 In addition, a Pipeline Research Council International project is compiling and analyzing Subpart W measurement data for development of new emission factors for the T&S sector. It is imperative that this wealth of new information be incorporated into the EPA's annual National Inventory.

Comment: INGAA believes EPA clearly and transparently should explain all changes to the methodology it relies upon to arrive at its National Inventory. All stakeholders should have the ability to understand the reason for any increases or decreases to the level of the National Inventory and changes attributable to the various sectors.

INGAA recommends that EPA revise the Planned Improvements section of the Draft GHG Report to define how EPA plans to integrate additional data, including Subpart W data, into its National Inventory, with a goal to use updated emission factors in the 2016 annual National Inventory report. EPA should work with all stakeholders, including INGAA, on this effort. A more accurate and timely National Inventory will help regulators, the industry and the public understand the GHG Inventory and sources of emissions.

Commenter: Wayne Evans

NorthWest Research Associates (NWRA)

Comment: GWPs should be 33 for 100 year and 82 for 20 year time scales from the IPCC 2013 report

Comment: A 20 year time scale is much more consistent with recent time trends in methane

Comment: Recent satellite data indicate that global methane in the NH is increasing again (since 2000). This may be due to unaccounted for methane leakage of gas fields during natural gas production.

Comment: There is a large discrepancy between Bottom up and Top down measurements of gas field leakage of methane. The bottom up measurements around gas wells indicate leakage rates of about 2% of production. The top down measurements from aircraft indicate that basin leakages are around 9 %. The discrepancy is about 7% of production. The satellite measurements are consistent with the aircraft measurements. The most likely explanation of this discrepancy is that the gas basins are leaking in a bulk sense. It has been shown that most gas deposits are overlain by layered coal beds. The boring of gas wells punctures the coal beds and results in large scale gas leaks on a scale larger than the individual gas wells. Fracking likely enhances this leakage process. The conclusion is that EPA is under reporting the gas field leaks to the UNFCCC: 2% instead of 9%! Similarly, other countries are under- reporting their gas production leakage rates.

Comment: If the gas field leakage rates were reported with 10% of production and a GWP of 82, then, the US total greenhouse budget would be about 30% higher. Similarly the GHG budget of most gas producing countries would be increased considerably more.

Comment: Until the combined gas field coal bed leakage effect can be resolved, one has to question as to whether natural gas is really a climate change friendly fuel.

Supplemental Material Received

Appendix A

Appendix A from the Center Biological Diversity comment on the U.S. Greenhouse Gas Emissions and Sinks: 1990-2013

Appendix B

American Forest & Paper Association 2013 Statistical Summary of Pulp, Paper and Paperboard

Appendix C

American Forest & Paper Association 2014 Sustainability Report

Appendix A

APPENDIX A

Table 1. The entries for source categories are directly from Table ES-2 (“Recent Trends in U.S. Greenhouse Gas Emissions and Sinks”) in the Draft GHG Inventory for 1990-2013 at ES-5. Data column 1 is a replicate of the last column in Table ES-2, which contains 2013 data. Data columns 2 and 3 in this table were compiled using IPCC AR5 100-year and 20-year GWPs, respectively for methane and nitrous oxide. These GWPs include climate-carbon feedbacks, as recommended by the AR5. GWPs for HFCs, PFCs, SF6 and NF3 were not altered. Methane GWPs: column 1 = 25; column 2 = 34 (biogenic) or 36 (fossil); column 3 = 86 (biogenic) or 87 (fossil). Data columns 4 through 6 reflect the percentage of total emissions (prior to removal of sinks) for each gas/source.

Gas/Source	**2013 (Inventory GWP) MMT CO2eq**	**2013 (AR5 100-yr GWP) MMT CO2eq**	**2013 (AR5 20-yr GWP) MMT CO2eq**	**Percent total GHG emissions (Inventory)**	**Percent total GHG emissions (AR5 100-yr)**	**Percent total GHG emissions (AR5 20-yr)**
CO2	**5,556.0**	**5,556.0**	**5,556.0**	**82.4**	**79.4**	**66.8**
Fossil Fuel Combustion	5,195.5	5,195.5	5,195.5	77.1	74.2	62.5
Electricity Generation	2,040.5	2,040.5	2,040.5	30.3	29.2	24.6
Transportation	1,754.0	1,754.0	1,754.0	26.0	25.1	21.1
Industrial	817.3	817.3	817.3	12.1	11.7	9.8
Residential	329.9	329.9	329.9	4.9	4.7	4.0
Commercial	221.5	221.5	221.5	3.3	3.2	2.7
U.S. Territories	32.3	32.3	32.3	0.5	0.5	0.4
Non-Energy Use of Fuels	133.0	133.0	133.0	2.0	1.9	1.6
Iron and Steel Production & Metallurgical Coke Production	52.3	52.3	52.3	0.8	0.7	0.6
Natural Gas Systems	37.8	37.8	37.8	0.6	0.5	0.5
Cement Production	36.1	36.1	36.1	0.5	0.5	0.4
Petrochemical Production	26.3	26.3	26.3	0.4	0.4	0.3
Lime Production	14.1	14.1	14.1	0.2	0.2	0.2
Ammonia Production	10.2	10.2	10.2	0.2	0.1	0.1
Incineration of Waste	10.1	10.1	10.1	0.1	0.1	0.1
Cropland Remaining Cropland	9.9	9.9	9.9	0.1	0.1	0.1
Petroleum Systems	6.0	6.0	6.0	0.1	0.1	0.1

Gas/Source	**2013 (Inventory GWP) MMT CO2eq**	**2013 (AR5 100-yr GWP) MMT CO2eq**	**2013 (AR5 20-yr GWP) MMT CO2eq**	**Percent total GHG emissions (Inventory)**	**Percent total GHG emissions (AR5 100-yr)**	**Percent total GHG emissions (AR5 20-yr)**
Urea Consumption for Non-Agricultural Purposes	4.7	4.7	4.7	0.1	0.1	0.1
Other Process Uses of Carbonates	4.4	4.4	4.4	0.1	0.1	0.1
Aluminum Production	3.3	3.3	3.3	0.0	0.0	0.0
Soda Ash Production and Consumption	2.7	2.7	2.7	0.0	0.0	0.0
Ferroalloy Production	1.8	1.8	1.8	0.0	0.0	0.0
Titanium Dioxide Production	1.6	1.6	1.6	0.0	0.0	0.0
Zinc Production	1.4	1.4	1.4	0.0	0.0	0.0
Phosphoric Acid Production	1.2	1.2	1.2	0.0	0.0	0.0
Glass Production	1.2	1.2	1.2	0.0	0.0	0.0
Carbon Dioxide Consumption	0.9	0.9	0.9	0.0	0.0	0.0
Wetlands Remaining Wetlands	0.8	0.8	0.8	0.0	0.0	0.0
Lead Production	0.5	0.5	0.5	0.0	0.0	0.0
Silicon Carbide Production and Consumption	0.2	0.2	0.2	0.0	0.0	0.0
Magnesium Production and Processing	+	+	+			
Land Use, Land-Use Change, and Forestry (Sink)	*-882.0*	*-882.0*	*-882.0*	*-13.1*	*-12.6*	*-10.6*
Wood Biomass and Ethanol Consumption	*283.3*	*283.3*	*283.3*	*4.2*	*4.0*	*3.4*
International Bunker Fuels	*99.8*	*99.8*	*99.8*	*1.5*	*1.4*	*1.2*
CH4	**654.1**	**911.9**	**2,259.1**	**9.7**	**13.0**	**27.2**
Enteric Fermentation	164.5	223.7	565.9	2.4	3.2	6.8
Natural Gas Systems	159.9	230.3	556.5	2.4	3.3	6.7

Gas/Source	**2013 (Inventory GWP) MMT CO2eq**	**2013 (AR5 100-yr GWP) MMT CO2eq**	**2013 (AR5 20-yr GWP) MMT CO2eq**	**Percent total GHG emissions (Inventory)**	**Percent total GHG emissions (AR5 100-yr)**	**Percent total GHG emissions (AR5 20-yr)**
Landfills	114.6	155.9	394.2	1.7	2.2	4.7
Coal Mining	64.6	93.0	224.8	1.0	1.3	2.7
Manure Management	61.4	83.5	211.2	0.9	1.2	2.5
Petroleum Systems	40.4	58.2	139.0	0.6	0.8	1.7
Wastewater Treatment	15.0	20.4	51.6	0.2	0.3	0.6
Rice Cultivation	8.3	11.3	28.6	0.1	0.2	0.3
Stationary Combustion	8.0	11.5	27.8	0.1	0.2	0.3
Abandoned Underground Coal Mines	6.2	8.9	21.6	0.1	0.1	0.3
Forest Land Remaining Forest Land	5.8	7.9	20.0	0.1	0.1	0.2
Mobile Combustion	2.1	3.0	7.3	0.0	0.0	0.1
Composting	2.0	2.7	6.9	0.0	0.0	0.1
Iron and Steel Production & Metallurgical Coke Production	0.7	1.0	2.4	0.0	0.0	0.0
Field Burning of Agricultural Residues	0.3	0.4	1.0	0.0	0.0	0.0
Petrochemical Production	0.1	0.1	0.3	0.0	0.0	0.0
Ferroalloy Production	+	+	+			
Silicon Carbide Production and Consumption	+	+	+			
Wetlands Remaining Wetlands	+	+	+			
Incineration of Waste	+	+	+			
International Bunker Fuelsc	0.1	0.1	0.3	0.0	0.0	0.0
N2O	**354.5**	**354.5**	**318.8**	**5.3**	**5.1**	**3.8**
Agricultural Soil Management	263.7	263.7	237.2	3.9	3.8	2.9

Gas/Source	**2013 (Inventory GWP) MMT CO2eq**	**2013 (AR5 100-yr GWP) MMT CO2eq**	**2013 (AR5 20-yr GWP) MMT CO2eq**	**Percent total GHG emissions (Inventory)**	**Percent total GHG emissions (AR5 100-yr)**	**Percent total GHG emissions (AR5 20-yr)**
Stationary Combustion	22.9	22.9	20.6	0.3	0.3	0.2
Mobile Combustion	18.4	18.4	16.5	0.3	0.3	0.2
Manure Management	17.3	17.3	15.6	0.3	0.2	0.2
Nitric Acid Production	10.7	10.7	9.6	0.2	0.2	0.1
Wastewater Treatment	4.9	4.9	4.4	0.1	0.1	0.1
N2O from Product Uses	4.2	4.2	3.8	0.1	0.1	0.0
Forest Land Remaining Forest Land	4.2	4.2	3.8	0.1	0.1	0.0
Adipic Acid Production	4.0	4.0	3.6	0.1	0.1	0.0
Settlements Remaining Settlements	1.8	1.8	1.6	0.0	0.0	0.0
Composting	1.8	1.8	1.6	0.0	0.0	0.0
Incineration of Waste	0.3	0.3	0.3	0.0	0.0	0.0
Semiconductor Manufacture	0.2	0.2	0.2	0.0	0.0	0.0
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.0	0.0	0.0
Wetlands Remaining Wetlands	+	+	+			
International Bunker Fuelsc	0.9	0.9	0.8	0.0	0.0	0.0
HFCs, PFCs, SF6 and NF3	**177.6**	**177.6**	**177.6**	**2.6**	**2.5**	**2.1**
HFCs	**164.3**	**164.3**	**164.3**	**2.4**	**2.3**	**2.0**
Substitution of Ozone Depleting Substancesd	158.6	158.6	158.6	2.4	2.3	1.9
HCFC-22 Production	5.5	5.5	5.5	0.1	0.1	0.1
Semiconductor Manufacture	0.2	0.2	0.2	0.0	0.0	0.0
Magnesium Production and	0.1	0.1	0.1	0.0	0.0	0.0

Gas/Source	**2013 (Inventory GWP) MMT CO2eq**	**2013 (AR5 100-yr GWP) MMT CO2eq**	**2013 (AR5 20-yr GWP) MMT CO2eq**	**Percent total GHG emissions (Inventory)**	**Percent total GHG emissions (AR5 100-yr)**	**Percent total GHG emissions (AR5 20-yr)**
Processing						
PFCs	**5.8**	**5.8**	**5.8**	**0.1**	**0.1**	**0.1**
Aluminum Production	3.0	3.0	3.0	0.0	0.0	0.0
Semiconductor Manufacture	2.9	2.9	2.9	0.0	0.0	0.0
SF6	**6.9**	**6.9**	**6.9**	**0.1**	**0.1**	**0.1**
Electrical Transmission and Distribution	5.1	5.1	5.1	0.1	0.1	0.1
Magnesium Production and Processing	1.4	1.4	1.4	0.0	0.0	0.0
Semiconductor Manufacture	0.4	0.4	0.4	0.0	0.0	0.0
NF3	**0.6**	**0.6**	**0.6**	**0.0**	**0.0**	**0.0**
Semiconductor Manufacture	0.6	0.6	0.6	0.0	0.0	0.0
Total	**6,742.2**	**7,000.0**	**8,311.5**			
Net Emissions (Sources and Sinks)	**5,860.2**	**6,118.0**	**7,429.5**			

Appendix B

2013 Statistical Summary

American Forest & Paper Association

StatMill

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August 2014

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Table of Contents

This is the fifty-second edition of AF&PA's Statistics of Paper, Paperboard, and Wood Pulp. This annual report covers the U.S. Paper Industry and includes a broad range of industry statistics. The source of data in this report is AF&PA, unless otherwise noted. Totals have not been adjusted to account for differences in rounding. Comments or suggestions as to how this report can be improved are welcome and should be directed to Karen Hibdon at 202-463-2724 or by email at Karen_Hibdon@afandpa.org.

Production, Imports, Exports and New Supply

TABLE 1 Paper and Paperboard Production, Imports, Exports and New Supply[1]

Year	Includes Wet Machine Board and Construction Grades: Production	Imports (Incl. Products)	Exports (Incl. Products)	New Supply [1]	Per Capita New Supply	Excludes Wet Machine Board and Construction Grades: Production	Imports (Incl. Products)	Exports (Incl. Products)	New Supply [1]	Per Capita New Supply
	thousands of short tons	thousands of short tons	thousands of short tons	thousands of short tons	pounds	thousands of short tons	thousands of short tons	thousands of short tons	thousands of short tons	pounds
1965	43,455	6,585	1,770	48,270	496.9	40,489	6,545	1,737	45,297	466.3
1970	51,670	7,115	2,817	55,968	545.9	48,719	7,057	2,779	52,997	516.9
1975	50,976	6,253	3,116	54,113	501.1	47,997	6,164	3,050	51,111	473.3
1980	63,600	8,780	5,214	67,166	589.9	61,042	8,304	5,148	64,198	563.8
1985	68,683	11,522	4,071	76,133	638.5	66,983	11,105	4,003	74,085	621.3
1990	80,551	13,148	6,796	86,902	694.9	78,785	13,006	6,787	85,004	679.7
1995	91,212	15,654	10,944	95,921	719.7	89,416	15,499	10,918	93,996	705.3
1997	96,807	15,856	13,162	99,501	729.2	95,044	15,657	13,137	97,565	715.0
1998	96,315	17,055	12,244	101,126	732.5	94,554	16,615	12,189	98,980	716.9
1999	98,648	18,488	11,820	105,316	754.2	97,020	18,063	11,765	103,318	739.8
2000	96,048	19,269	12,507	102,810	728.7	94,491	18,876	12,436	100,932	715.3
2001	90,384	18,513	11,503	97,395	683.2	88,913	18,136	11,456	95,592	670.6
2002	91,112	19,433	11,596	98,949	687.3	89,687	19,149	11,506	97,331	676.0
2003	89,813	20,064	11,867	98,010	674.1	88,388	19,826	11,797	96,417	663.1
2004	93,408	21,144	12,670	101,883	693.9	91,901	20,894	12,574	100,220	682.6
2005	92,610	20,438	13,434	99,613	665.4	91,108	20,204	13,311	98,001	654.6
2006	93,720	20,293	13,349	100,664	664.6	92,224	20,078	13,254	99,048	654.0
2007	92,956	18,634	14,582	97,008	636.5	91,667	18,480	14,501	95,647	627.6
2008	88,445	16,870	15,477	89,838	590.9	87,401	16,789	15,382	88,808	584.1
2009	79,062	13,446	13,797	78,710	512.8	78,298	13,359	13,739	77,918	507.6
2010	83,702	13,740	15,657	81,784	529.8	82,968	13,639	15,581	81,025	524.9
2011	82,725	13,171	16,452	79,444	509.9	82,003	13,057	16,380	78,680	505.0
2012	81,832	12,555	15,768	78,619	500.9	81,051	12,507	15,690	77,868	496.1
2013	81,326	13,129	15,694	77,761	492.0	80,477	13,089	15,644	76,922	486.6

[1] *New Supply is Production plus Imports less Exports (including Imports and Exports of Products).*

Sources: Production: AF&PA, Imports and Exports: U.S. Bureau of the Census, U.S. Population Estimate: U.S. Bureau of the Census.

Paper and Board Production 2012

TABLE 2 A Paper and Board Production for 2012

thousands of short tons

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Newsprint [1]	260	253	280	268	274	268	270	275	239	256	232	263	3,136
Printing & Writing	1,581	1,535	1,597	1,469	1,574	1,551	1,533	1,611	1,523	1,618	1,479	1,399	18,471
Uncoated Mechanical (s)	151	147	147	139	150	151	139	138	120	139	124	111	1,655
Total Coated Papers (s)	598	575	592	545	593	618	594	632	635	659	596	547	7,184
Coated Free Sheet (s)	316	301	319	298	316	316	322	358	353	380	332	299	3,911
Coated Mechanical (s)	282	273	274	247	276	301	272	274	282	279	265	248	3,273
Uncoated Free Sheet (s)	773	750	791	731	768	718	735	769	707	753	696	687	8,877
Other Printing & Writing Papers (s)	60	63	68	54	63	65	65	72	61	66	62	55	754
Tissue Paper	619	591	621	595	598	580	626	630	582	617	598	626	7,283
Total Packaging & Other Paper	365	348	373	352	362	352	362	357	347	353	339	341	4,252
Unbleached Kraft Papers (s)	113	117	124	116	121	113	118	115	115	113	103	102	1,372
Bleached Kraft Papers (s)	17	14	18	19	17	20	20	17	16	15	18	16	207
Specialty Packaging & Other [2]	235	217	231	217	224	218	224	224	216	225	218	223	2,673
TOTAL PAPER PRODUCTION	**2,826**	**2,727**	**2,871**	**2,683**	**2,808**	**2,751**	**2,790**	**2,872**	**2,691**	**2,844**	**2,648**	**2,629**	**33,142**
TOTAL PAPER OPERATING RATE	**88%**	**91%**	**90%**	**87%**	**88%**	**90%**	**89%**	**91%**	**88%**	**91%**	**87%**	**84%**	**89%**
Containerboard	2,888	2,735	2,931	2,697	2,887	2,843	2,915	2,975	2,830	2,908	2,867	2,927	34,403
Total Linerboard	2,051	1,934	2,058	1,885	2,036	2,043	2,078	2,109	2,005	2,072	2,018	2,059	24,349
Corrugating Medium	837	801	872	813	851	799	837	866	826	836	849	868	10,054
Boxboard	1,125	1,098	1,138	1,127	1,159	1,141	1,136	1,158	1,083	1,111	1,118	1,114	13,506
Total Folding Boxboard	581	570	590	577	604	589	587	584	550	565	588	584	6,969
Unbleached Kraft	211	209	204	215	215	208	220	205	182	186	199	212	2,465
Solid Bleached	177	183	193	178	205	200	178	186	176	184	198	191	2,251
Recycled	193	178	192	184	184	182	189	193	193	194	191	181	2,254
Liquid Pkg. & Food Service	255	253	250	255	250	258	251	276	247	251	247	257	3,052
Other Boxboard	289	275	298	294	305	294	298	298	285	295	282	273	3,484
TOTAL BOARD PRODUCTION	**4,013**	**3,833**	**4,069**	**3,825**	**4,046**	**3,983**	**4,051**	**4,133**	**3,913**	**4,019**	**3,985**	**4,041**	**47,909**
TOTAL BOARD OPERATING RATE	**93%**	**95%**	**94%**	**91%**	**94%**	**95%**	**94%**	**96%**	**94%**	**93%**	**95%**	**94%**	**94%**
TOTAL PAPER & BOARD PRODUCTION	**6,839**	**6,560**	**6,940**	**6,508**	**6,854**	**6,734**	**6,841**	**7,005**	**6,604**	**6,862**	**6,633**	**6,670**	**81,051**
TOTAL PAPER & BOARD OPERATING RATE	**91%**	**93%**	**92%**	**90%**	**92%**	**93%**	**92%**	**94%**	**91%**	**92%**	**92%**	**90%**	**92%**

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[1] Newsprint data are compiled by Pulp and Paper Products Council.

[2] Estimated by AF&PA

(s) - Shipments. Shipment data used where production data are not available.

Paper and Board Production 2013

TABLE 2 B Paper and Board Production for 2013

thousands of short tons

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Newsprint [1]	257	228	235	212	228	216	220	230	227	228	213	229	2,723
Printing & Writing	1,547	1,377	1,508	1,469	1,474	1,451	1,537	1,550	1,532	1,613	1,407	1,447	17,912
Uncoated Mechanical (s)	132	115	130	131	132	125	136	133	131	139	141	135	1,579
Total Coated Papers (s)	591	504	562	539	548	561	582	595	619	626	529	528	6,783
Coated Free Sheet (s)	337	285	314	312	310	309	327	339	349	365	294	287	3,829
Coated Mechanical (s)	254	219	248	226	238	251	256	256	270	261	235	241	2,954
Uncoated Free Sheet (s)	764	700	755	739	733	704	757	754	721	784	677	723	8,811
Other Printing & Writing Papers (s)	61	57	61	61	61	61	62	67	61	66	60	61	739
Tissue Paper	635	586	636	625	631	625	643	648	613	627	601	619	7,490
Total Packaging & Other Paper	378	332	366	354	350	344	357	357	340	350	328	345	4,202
Unbleached Kraft Papers (s)	123	105	117	112	106	109	113	113	107	111	104	113	1,333
Bleached Kraft Papers (s)	21	16	17	20	21	21	21	22	19	19	10	12	220
Specialty Packaging & Other [2]	235	212	232	222	222	214	223	222	214	220	215	221	2,650
TOTAL PAPER PRODUCTION	**2,817**	**2,523**	**2,744**	**2,661**	**2,684**	**2,636**	**2,757**	**2,784**	**2,712**	**2,819**	**2,550**	**2,640**	**32,328**
TOTAL PAPER OPERATING RATE	**90%**	**90%**	**88%**	**90%**	**87%**	**88%**	**89%**	**90%**	**91%**	**91%**	**85%**	**86%**	**89%**
Containerboard	2,973	2,662	2,854	2,806	3,010	2,953	3,065	3,090	2,817	2,933	2,720	2,838	34,721
Total Linerboard	2,127	1,898	2,044	1,989	2,158	2,120	2,189	2,202	2,007	2,095	1,951	2,035	24,815
Corrugating Medium	846	765	810	818	852	833	876	888	810	838	769	802	9,906
Boxboard	1,106	1,048	1,106	1,132	1,140	1,142	1,152	1,180	1,106	1,101	1,105	1,109	13,429
Total Folding Boxboard	571	554	560	571	586	579	591	609	564	544	568	563	6,860
Unbleached Kraft	214	199	197	213	222	212	208	215	189	181	211	206	2,467
Solid Bleached	164	177	169	174	174	192	186	197	185	170	171	183	2,143
Recycled	193	178	194	184	190	175	197	197	189	192	187	174	2,250
Liquid Pkg. & Food Service	249	238	247	257	249	266	262	261	250	243	259	274	3,054
Other Boxboard	287	256	300	304	305	297	299	310	292	315	278	273	3,515
TOTAL BOARD PRODUCTION	**4,080**	**3,711**	**3,960**	**3,938**	**4,150**	**4,095**	**4,216**	**4,270**	**3,923**	**4,035**	**3,826**	**3,947**	**48,150**
TOTAL BOARD OPERATING RATE	**94%**	**96%**	**93%**	**95%**	**96%**	**97%**	**96%**	**97%**	**95%**	**94%**	**91%**	**90%**	**95%**
TOTAL PAPER & BOARD PRODUCTION	**6,897**	**6,234**	**6,704**	**6,599**	**6,834**	**6,731**	**6,974**	**7,054**	**6,634**	**6,853**	**6,376**	**6,587**	**80,477**
TOTAL PAPER & BOARD OPERATING RATE	**93%**	**93%**	**91%**	**93%**	**92%**	**93%**	**93%**	**94%**	**93%**	**93%**	**88%**	**89%**	**92%**

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[1] *Newsprint data are compiled by Pulp and Paper Products Council.*

[2] *Estimated by AF&PA*

(s) - *Shipments. Shipment data used where production data are not available.*

Total Paper Shipments

TABLE 3 A Total Paper Shipments by Grade

thousands of short tons

						Coated Free Sheet							Coated Mechanical		
								Coated Two Sides							
Year	Paper	Newsprint	Total Printing-Writing and Related [1]	Total Printing-Writing [2]	Total Coated	Total Coated Free Sheet	Coated One Side	#1	#2 [3]	#3 [3]	#4 [3]	Job Lot	Total Mechanical	#3 + #4 [3]	#5 + Job Lot [3]
1995	42,899	7,002	25,405	23,922	8,795	4,371	470	427	1,094	1,894	293	194	4,424	772	3,652
1996	42,482	6,949	24,869	23,375	8,184	4,363	434	428	1,052	1,884	335	230	3,821	676	3,145
1997	44,697	7,215	26,628	25,066	9,317	4,811	430	452	1,167	2,391	166	206	4,506	825	3,681
1998	44,761	7,250	26,501	24,969	9,302	4,932	410	481	1,095	2,612	136	198	4,370	1,119	3,252
1999	45,979	7,179	27,156	25,569	9,580	5,105	391	458	1,092	2,877	67	220	4,475	1,270	3,206
2000	45,519	7,241	26,935	25,344	9,615	4,993	428	441	1,102	2,744	74	204	4,622	1,479	3,143
2001	42,103	6,360	24,433	23,050	8,876	4,486	399	311	1,057	2,408	105	206	4,390	1,556	2,834
2002 [5]	41,560	5,784	24,491	23,058	8,962	4,481	383	271	1,149	2,318	123	238	4,481	1,613	2,868
2003	40,370	5,676	23,713	22,382	8,708	4,191	347	214	1,131	2,298 [4]		200	4,517	1,583	2,934
2004	41,816	5,618	25,021	23,602	9,389	4,652	341	215	1,541	2,320		234	4,737	1,662	3,076
2005	41,397	5,392	24,494	23,205	9,330	4,626	329	188	1,481	2,409		219	4,704	1,721	2,983
2006	41,810	5,225	24,971	23,705	9,485	4,968	306	194	1,428	2,849		191	4,517	1,706	2,811
2007	41,267	4,921	24,887	23,688	9,660	4,997	295	221	1,461	2,837		182	4,663	1,879	2,784
2008	38,955	4,623	22,952	21,817	8,590	4,439	315	173	1,299	2,442		210	4,151	1,791	2,360
2009	33,808	3,298	19,370	18,470	7,009	3,638	307	115	843	2,135		238	3,370	1,361	2,009
2010	35,508	3,429	20,467	19,596	7,911	4,146	349	108	881	2,546		263	3,765	1,537	2,227
2011	34,344	3,267	19,470	18,698	7,442	3,988	355	118	859	2,446		210	3,454	1,490	1,963
2012	33,142	3,136	18,471	17,717	7,184	3,911	373		916 [6]	2,419		202	3,273	1,425	1,849
2013	32,328	2,723	17,912	17,174	6,783	3,829	338		903	2,404		183	2,954	1,263	1,691

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[1] *Total of Uncoated Mechanical, Coated Paper, Uncoated Free Sheet, Cotton Fiber, and Bristols.*

[2] *Total of Uncoated Mechanical, Coated Printing and Uncoated Free Sheet.*

[3] *Data from 1997 forward affected by grade reclassifications.*

[4] *Coated Two Sides Nos. 3 & 4 Free Sheet have been combined to prevent disclosure.*

[5] *Effective 2002 coated paper brightness levels have changed, which may limit comparability with prior periods.*

[6] *Coated Two Sides Nos. 1 & 2 Free Sheet have been combined to prevent disclosure.*

Total Paper Shipments

TABLE 3 B Total Paper Shipments by Grade

thousands of short tons

	Uncoated Mechanical			Uncoated Free Sheet															
													Offset & Opaque			Cover & Text			
Year	Total Uncoated Mechanical	Super-calendered	Other	Total Uncoated Free Sheet	Bond & Writing [8]	Ledger [9]	Form Bond	Carbon-less [10]	Tablet	M.F., E.F. & Super-calendered	Papeterie & Wedding [11]	Envelope	Total	Rolls	Sheets	Total	Cover	Text	Other Uncoated Free Sheet [7]
1995	2,130	620	1,510	12,997	4,076	34	1,710	891	352	57	55	1,295	3,431	2,455	976	513	219	294	584
1996	2,028	568	1,461	13,163	4,289	28	1,747	829	370	54	57	1,351	3,479	2,571	908	501	222	278	460
1997	2,068	612	1,456	13,681	4,621	32	1,688	812	356	53	45	1,438	3,626	2,617	1,010	509	240	269	501
1998	2,062	564	1,454	13,605	4,780	31	1,594	704	309	65	39	1,418	3,749	2,750	999	437	200	237	479
1999	1,952	557	1,395	14,037	4,984	27	1,567	704	383	110	35	1,464	3,785	2,785	1,000	438	196	242	541
2000	1,832	578	1,253	13,898	4,985	21	1,378	817	335	116	23	1,513	3,862	2,833	1,029	429	150	279	419
2001	1,525	534	991	12,649	4,907	18	1,248	707	231	87	21	1,392	3,290	2,396	893	383	153	229	367
2002	1,668	687	981	12,428	5,003	17	1,204	648	208	50	20	1,422	3,111	2,310	801	344	158	186	400
2003	1,412	641	771	12,262	5,007	22	1,127	611	252	52	22	1,366	3,102	2,362	741	304	144	161	397
2004	1,658	675	983	12,555	5,171	16	1,103	585	274	116	21	1,452	3,049	2,323	727	299	148	151	469
2005	1,859	759	1,100	12,016	5,144	17	1,041	591	211	111		1,384	2,875	2,191	684	286	142	143	355
2006	1,916	735	1,181	12,304	5,268	16	1,002	536	228	82		1,389	2,933	2,150	783	318	175	143	532
2007	2,092	753	1,339	11,935	5,076		1,003	523	213			1,346	2,866	2,081	785	304	149	155	605
2008	2,282	708	1,574	10,946	4,877		963	481	187			1,228	2,546	1,815	730	234	132	102	429
2009	1,757	610	1,147	9,704	4,394		717	409	183			1,102	1,957	1,388	569	159	85	74	783
2010	2,130	678	1,452	9,556	4,191		714	393	202			1,059	2,097	1,460	638	172	94	78	727
2011	1,949	661	1,287	9,308	4,040		721	364	231			1,032	1,974	1,388	587	171	85	86	775
2012	1,655	531	1,125	8,877	3,852		676	322	210			971	1,818	1,281	538	123	61	62	905
2013	1,579	533	1,046	8,811	3,813		630	303	254			947	1,776	1,259	517	179	91	89	909

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[7] *Includes All Other Uncoated Free Sheet, Other Technical, Direct Line, Air Dried, Manifold and Thin Paper. Includes Papeterie beginning 2005. Includes M.F., E.F. & Supercalendered and technical starting in 2007.*

[8] *Mimeo and Duplicating combined with Bond & Writing.*

[9] *Combined with Bond & Writing in 2007.*

[10] *Includes both carbonless paper and base stock for carbonless coating.*

[11] *Combined with Other Uncoated Free Sheet in 2005.*

Total Paper Shipments

TABLE 3 C Total Paper Shipments by Grade

thousands of short tons

			Packaging and Industrial Converting					
Year	Total Cotton Fiber	Total Bleached Bristols	Total	Total Kraft Paper	Unbleached Kraft Papers	Bleached Packaging Papers	Specialty Packaging & Industrial	Tissue
1995	123	1,361	4,282	2,412	2,025	387	1,870	6,210
1996	133	1,360	4,399	2,348	1,971	377	2,051	6,264
1997	114	1,447	4,425	2,301	1,901	400	2,124	6,429
1998	122	1,409	4,425	2,174	1,860	314	2,251	6,585
1999	117	1,470	4,796	2,231	1,916	315	2,565	6,847
2000	104	1,487	4,432	2,035	1,707	329	2,396	6,911
2001	86	1,297	4,287	1,891	1,601	290	2,396	7,024
2002	83	1,350	4,159	1,835	1,545	291	2,323	7,127
2003	76	1,255	3,887	1,636	1,385	250	2,252	7,094
2004	71	1,348	4,066	1,654	1,400	254	2,412	7,111
2005	69	1,221	4,101	1,597	1,362	235	2,504	7,409
2006	63	1,202	4,111	1,579	1,370	209	2,532	7,503
2007	61	1,138	4,111	1,651	1,458	194	2,460	7,348
2008	49	1,086	4,147	1,687	1,492	195	2,460	7,233
2009	43	857	3,863	1,403	1,236	167	2,460	7,276
2010	23	848	4,303	1,620	1,435	185	2,683	7,309
2011	20	752	4,318	1,677	1,462	215	2,641	7,290
2012	12	742	4,252	1,579	1,372	207	2,673	7,283
2013	14	725	4,202	1,553	1,333	220	2,650	7,490

Paperboard Production

TABLE 4 Total Paperboard Production by Grade

thousands of short tons

	All Grades	Containerboard - Domestic			Boxboard - Domestic				All Other - Domestic				Exports
Year	Total	Total	Linerboard	Corrugating Material [1]	Total	Folding	Set-Up	Liquid Packaging & Food Service	Total	Gypsum Wallboard Facing	Tube, Can and Drum	Balance of All Other [2]	Total
1995	46,548	28,600	19,773	8,827	8,502	6,384	282	1,835	4,867	1,479	1,549	1,839	4,580
1996	47,935	28,975	19,770	9,205	8,469	6,476	250	1,742	4,911	1,552	1,572	1,788	5,580
1997	50,347	30,049	20,477	9,572	8,518	6,495	254	1,770	5,066	1,570	1,634	1,862	6,714
1998	49,793	30,279	20,911	9,369	8,603	6,666	245	1,692	5,123	1,579	1,574	1,970	5,788
1999	51,041	31,732	21,963	9,769	8,790	6,744	285	1,761	5,100	1,602	1,641	1,857	5,419
2000	48,972	30,571	20,920	9,651	8,801	6,705	235	1,861	4,666	1,416	1,628	1,622	4,934
2001	46,809	29,271	19,954	9,317	8,485	6,437	218	1,830	4,384	1,448	1,446	1,491	4,669
2002	48,126	30,486	20,823	9,663	8,379	6,349	206	1,823	4,361	1,429	1,509	1,423	4,901
2003	48,018	30,191	20,471	9,720	8,331	6,380	216	1,736	4,541	1,556	1,492	1,493	4,955
2004	50,085	31,912	21,614	10,298	8,441	6,340	198	1,903	4,751	1,625	1,583	1,543	4,981
2005	49,711	31,430	21,218	10,212	8,498	6,326	184	1,988	4,614	1,710	1,491	1,414	5,169
2006	50,415	31,986	21,882	10,104	8,550	6,340	187	2,024	4,494	1,616	1,485	1,394	5,385
2007	50,400	31,885	22,048	9,837	8,586	6,399	169	2,017	4,225	1,437	1,442	1,346	5,705
2008	48,446	30,288	20,776	9,512	8,356	6,218	141	1,997	3,819	1,203	1,368	1,248	5,983
2009	44,491	27,593	18,861	8,732	7,766	5,793	102	1,871	3,257	908	1,206	1,143	5,875
2010	47,460	29,794	20,523	9,271	8,047	5,950	96	2,001	3,360	865	1,323	1,172	6,259
2011	47,652	30,005	20,566	9,439	8,107	6,021	84	2,002	3,313	893	1,290	1,130	6,227
2012 R	47,909	30,080	20,485	9,595	8,076	5,961	75	2,040	3,385	1,023	1,305	1,057	6,368
2013	48,150	30,288	20,807	9,481	7,908	5,828	75	2,005	3,420	1,007	1,339	1,074	6,535

[1] *Includes Container Chip & Filler Board.*

[2] *Beginning 2005, Balance of All Other includes Unbleached Kraft Tube Can and Drum. Beginning 2009, Balance of All Other includes Solid Bleached Linerboard. This is required to meet Antitrust Safe Harbor guidelines.*

R - Revised

Unbleached Kraft Paperboard Production

TABLE 5 A Unbleached Kraft Paperboard Production *thousands of short tons*

Year	Total All Grades	For Domestic Use Total Domestic	For Domestic Use Linerboard	For Domestic Use Folding	For Domestic Use All Other	For Export
1995	22,730	19,433	17,686	1,452	296	3,297
1996	22,174	17,928	16,108	1,473	347	4,246
1997	23,222	18,111	16,338	1,432	341	5,111
1998	23,198	18,929	16,903	1,662	364	4,269
1999	23,113	19,376	17,459	1,637	281	3,737
2000	21,796	18,430	16,486	1,716	228	3,366
2001	20,437	17,480	15,581	1,738	161	2,958
2002	21,086	17,954	16,024	1,740	189	3,132
2003	21,730	18,258	16,298	1,784	176	3,472
2004	22,665	19,275	17,270	1,789	217	3,390
2005	22,578	19,029	16,962	1,854	212	3,549
2006	23,415	19,663	17,623	1,884	156	3,752
2007	23,544	19,676	17,482	2,063	132	3,868
2008	22,169	18,251	16,186	1,975	90	3,918
2009	20,549	16,598	14,694	1,833	71	3,951
2010	21,355	17,343	15,486	1,857	-	4,012
2011	21,615	17,464	15,519	1,945	-	4,151
2012	21,844	17,632	15,668	1,964	-	4,212
2013	21,998	17,666	15,697	1,969	-	4,332

Source: AF&PA's Containerboard Annual Summary & Basis Weight Survey

Solid Bleached Paperboard Production

TABLE 5 B Solid Bleached Paperboard Production *thousands of short tons*

Year	Total All Grades	For Domestic Use Total Domestic	For Domestic Use Folding	For Domestic Use Liquid Packaging & Food Service	For Domestic Use Other Packaging & Non-Packaging[1]	For Export
1995	5,157	4,135	2,068	1,835	231	1,022
1996	5,082	4,090	2,088	1,742	259	992
1997	5,377	4,200	2,112	1,770	318	1,177
1998	5,338	4,216	2,145	1,692	379	1,122
1999	5,572	4,448	2,259	1,761	429	1,124
2000	5,297	4,213	2,223	1,861	129	1,084
2001	5,187	4,069	2,083	1,830	156	1,118
2002	5,180	4,027	2,057	1,823	146	1,153
2003	5,237	4,023	2,127	1,736	160	1,214
2004	5,506	4,178	2,105	1,903	169	1,328
2005	5,584	4,250	2,129	1,988	132	1,335
2006	5,620	4,287	2,105	2,024	159	1,333
2007	5,720	4,265	2,069	2,017	178	1,456
2008	5,689	4,194	2,031	1,997	167	1,495
2009	5,288	3,886	1,792	1,871	223	1,402
2010	5,616	4,068	1,829	2,001	238	1,548
2011	5,522	4,038	1,806	2,002	230	1,484
2012 R	5,482	3,978	1,765	2,040	173	1,504
2013	5,401	3,834	1,630	2,005	199	1,567

Source: AF&PA's Paperboard Annual Statistical Summary and Time Series. R - Revised

[1] *Beginning 2009, Other Packaging and Non-Packaging includes Solid Bleached Linerboard.*

TABLE 5 C Semichemical Paperboard Production *thousands of short tons*

		For Domestic Use			
Year	Total All Grades	Total Domestic	Corrugating	All Other	For Export
1995	5,673	5,536	5,532	3.3	138
1996	5,619	5,414	5,410	3.5	206
1997	6,047	5,779	5,778	1.0	267
1998	5,894	5,665	5,665	-	229
1999	6,010	5,711	5,711	-	299
2000	5,948	5,686	5,686	-	263
2001	5,579	5,267	5,266	0.5	313
2002	5,838	5,522	5,522	0.4	316
2003	6,096	5,962	5,962	0.1	134
2004	6,529	6,373	6,373	-	156
2005	6,414	6,239	6,239	-	175
2006	6,224	6,022	6,022	-	202
2007	6,160	5,863	5,863	-	298
2008	5,819	5,439	5,439	-	380
2009	5,213	4,858	4,858	-	355
2010	5,443	4,955	4,955	-	488
2011	5,431	5,025	5,025	-	406
2012	5,414	5,016	5,016	-	398
2013	5,313	4,926	4,926	-	387

Source: AF&PA's Containerboard Annual Summary & Basis Weight Survey

TABLE 5 D Recycled Paperboard Production *thousands of short tons*

		For Domestic Use								
Year	Total All Grades	Total Domestic	Linerboard	Corrugating Material [1]	Folding	Set-Up	Tube, Can & Drum	Gypsum Wallboard Facing	Panelboard and Other Uses	For Export
1995	12,837	12,714	1,936	3,294	2,864	282	1,491	1,479	1,367	123
1996	14,906	14,770	3,508	3,795	2,916	250	1,499	1,552	1,250	136
1997	15,530	15,370	3,967	3,793	2,950	254	1,569	1,570	1,267	159
1998	15,214	15,047	3,858	3,704	2,858	245	1,495	1,579	1,307	168
1999	16,206	15,946	4,364	4,058	2,849	285	1,582	1,602	1,206	260
2000	15,791	15,569	4,294	3,965	2,767	235	1,615	1,416	1,277	221
2001	15,495	15,215	4,263	4,051	2,616	218	1,430	1,448	1,189	281
2002	15,906	15,607	4,683	4,141	2,552	206	1,487	1,429	1,110	300
2003	14,832	14,697	4,050	3,759	2,468	216	1,474	1,556	1,176	135
2004	15,237	15,129	4,195	3,925	2,446	198	1,544	1,625	1,196	108
2005	15,055	14,945	4,176	3,973	2,343	184	1,491	1,710	1,070	110
2006	15,071	14,973	4,174	4,082	2,351	187	1,485	1,616	1,079	98
2007	14,891	14,808	4,482	3,974	2,268	169	1,442	1,437	1,036	83
2008	14,690	14,501	4,513	4,073	2,212	141	1,368	1,203	991	189
2009	13,439	13,272	4,166	3,874	2,168	102	1,206	908	848	167
2010	15,045	14,835	5,037	4,316	2,264	96	1,323	865	934	210
2011	15,090	14,904	5,048	4,414	2,269	84	1,290	893	906	186
2012	15,167	14,913	4,817	4,578	2,232	75	1,305	1,023	883	254
2013	15,439	15,191	5,110	4,555	2,229	75	1,339	1,007	876	248

Source: AF&PA's Paperboard Annual Statistical Summary and Time Series

[1] *Includes Container Chip & Filler Board*

Paper New Supply

TABLE 6 A Paper New Supply [1]

thousands of short tons

			Printing-Writing and Related					Packaging and Industrial Converting			
Year	Total Paper	Newsprint	Printing-Writing Papers	Uncoated Mechanical	Total Coated	Uncoated Free Sheet	Other Printing-Writing Related [2]	Total Packaging and Industrial Converting Papers	Unbleached Kraft	Other	Tissue
1995	52,769	12,762	29,550	4,967	9,720	13,355	1,508	4,241	2,034	2,207	6,215
1996	50,687	11,768	28,300	4,456	8,853	13,476	1,515	4,325	1,928	2,397	6,294
1997	54,149	12,612	30,751	4,818	10,263	14,080	1,591	4,265	1,801	2,465	6,521
1998	55,132	12,801	31,384	4,983	10,584	14,213	1,604	4,285	1,731	2,553	6,662
1999	57,304	13,087	32,528	5,182	10,870	14,739	1,737	4,711	1,820	2,890	6,978
2000	57,125	12,921	32,986	5,480	11,196	14,510	1,799	4,273	1,637	2,636	6,945
2001	53,464	11,469	30,617	5,227	10,226	13,430	1,733	4,307	1,601	2,706	7,071
2002	53,663	11,176	31,088	5,470	10,663	13,452	1,502	4,202	1,548	2,655	7,197
2003	53,198	11,050	31,007	5,538	10,829	13,265	1,375	3,957	1,320	2,637	7,184
2004	54,876	10,841	32,679	5,881	11,868	13,482	1,448	4,137	1,349	2,788	7,219
2005	53,693	10,123	31,988	6,205	11,701	12,765	1,318	4,048	1,178	2,870	7,535
2006	52,970	9,489	31,784	5,598	12,193	12,805	1,188	4,098	1,221	2,877	7,600
2007	50,881	8,348	31,045	6,206	11,564	12,155	1,121	4,072	1,298	2,774	7,416
2008	46,711	7,249	28,060	6,024	9,846	11,150	1,040	4,046	1,301	2,745	7,356
2009	39,374	5,258	23,028	4,820	7,610	9,761	837	3,663	1,002	2,661	7,425
2010	40,342	4,996	23,732	4,818	8,420	9,653	841	4,184	1,148	3,036	7,430
2011	38,504	4,570	22,457	4,432	7,983	9,333	708	3,999	994	3,005	7,478
2012	37,026	4,405	21,084	3,737	7,857	8,845	646	4,072	1,108	2,964	7,465
2013	36,539	3,921	20,823	3,840	7,501	8,876	607	4,134	1,123	3,011	7,660

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[1] *New Supply is Production plus Imports less Exports. If Production is not available then annual shipment figures are used. New Supply is calculated using Import/Export figures from the U.S. Bureau of the Census, unless preferred alternative Import/Export data is available (see page 26).*

[2] *Imports/Exports of Other Printing-Writing Related may include a small amount of tonnage used for wallpaper base and other miscellaneous uses.*

[3] *U.S. Bureau of the Census is the sole source for Import/Export data used to calculate New Supply of Paper, Paperboard and Products, and Total New Supply Including Converted Products.*

R - Revised

Paperboard New Supply

TABLE 6 B Paperboard New Supply [1]

thousands of short tons

	Paperboard					
Year	Total Paperboard	Unbleached Kraft	Semichemical	Bleached Board	Recycled	Construction and Other
1995	43,387	19,774	5,841	4,286	13,485	1,925
1996	43,383	17,934	5,689	4,244	15,516	2,108
1997	45,130	18,477	6,089	4,372	16,192	1,936
1998	45,672	19,313	5,974	4,366	16,020	2,147
1999	47,592	19,872	6,118	4,588	17,014	1,999
2000	46,021	18,958	6,020	4,353	16,690	1,877
2001	44,088	18,008	5,598	4,179	16,303	1,801
2002	45,291	18,491	5,829	4,142	16,828	1,617
2003	44,947	18,709	6,235	4,146	15,856	1,592
2004	47,201	19,825	6,678	4,326	16,372	1,663
2005	46,505	19,508	6,488	4,329	16,180	1,612
2006	47,107	20,083	6,324	4,372	16,327	1,616
2007	46,608	20,054	6,151	4,349	16,055	1,361
2008	44,246	18,721	5,716	4,374	15,435	1,030
2009	40,194	16,940	4,968	4,017	14,269	792
2010	43,061	17,717	5,081	4,193	16,071	759
2011	43,215	17,891	5,148	4,145	16,031	764
2012 R	43,244	18,042	5,122	4,094	15,986	751
2013	43,541	18,184	5,055	3,965	16,336	839

See footnotes on page 12.

Total New Supply

TABLE 6 C Total New Supply [1]

thousands of short tons

Year	Total All Grades Including Construction Grades, Excluding Converted Products	Paper, Paperboard and Converted Products [3]	Total All Grades Including Construction Grades and Converted Products [3]
1995	98,081	93,996	95,921
1996	96,178	92,535	94,643
1997	101,215	97,565	99,501
1998	102,951	98,980	101,126
1999	106,895	103,318	105,316
2000	105,023	100,932	102,808
2001	99,353	95,592	97,393
2002	100,570	97,331	98,948
2003	99,737	96,417	98,010
2004	103,740	100,220	101,883
2005	101,811	98,001	99,613
2006	101,693	99,048	100,664
2007	98,851	95,647	97,008
2008	91,986	88,808	89,838
2009	80,360	77,918	78,710
2010	84,162	81,025	81,784
2011	82,483	78,680	79,444
2012 R	81,022	77,868	78,619
2013	80,919	77,922	78,761

See footnotes on page 12.

TABLE 7 State Data 2013

thousands of short tons

Geographic Areas	Recovered Paper Consumption [1]	Total Paper & Paperboard Capacity [2]
UNITED STATES, TOTAL	**30,143**	**87,349**
Alabama	1,843	7,973
Arkansas	(D)	3,096
California	1,162	1,309
Connecticut	579	701
Florida	(D)	3,126
Georgia	2,352	7,526
Illinois	244	282
Indiana	735	716
Kentucky	(D)	1,818
Louisiana	1,853	7,538
Maine	(D)	3,484
Massachusetts	263	369
Michigan	1,467	3,314
Minnesota	790	2,216
Mississippi	208	1,890
Missouri	101	(D)
New Hampshire	62	(D)
New York	2,228	2,953
North Carolina	316	1,757
Ohio	1,063	1,650
Oklahoma	1,282	2,459
Oregon	1,046	2,680
Pennsylvania	836	2,455
South Carolina	936	4,733
Tennessee	931	3,010
Texas	631	2,536
Vermont	154	211
Virginia	1,583	3,901
Washington	1,211	4,697
Wisconsin	2,255	5,505
Mountain Region [3]	364	1,051
States Not Listed[4]	1,572	1,884

Note: (D) - *Withheld to avoid disclosure.*

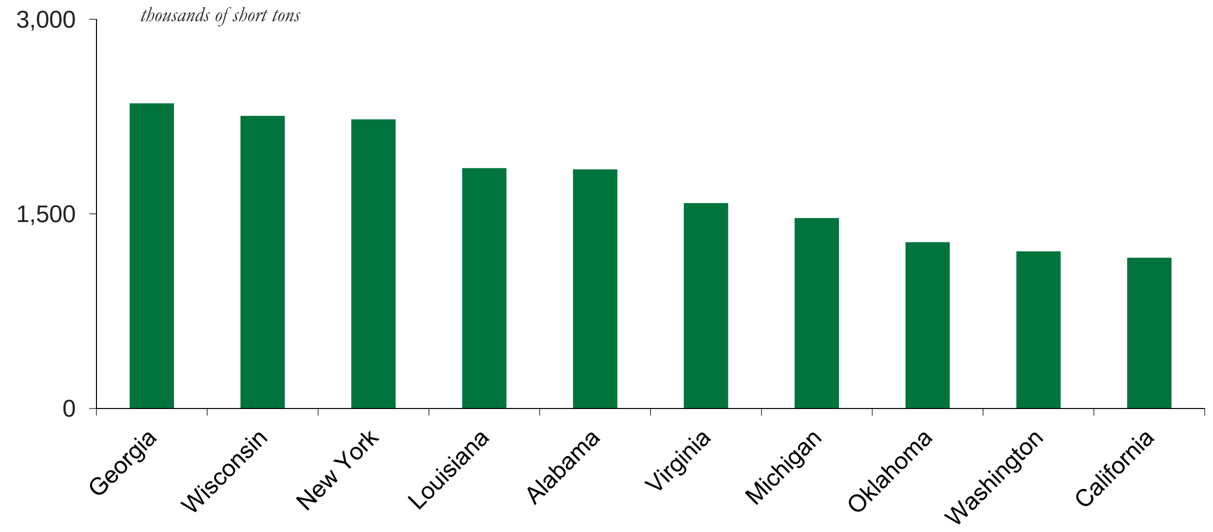
[1] *Includes construction grades and molded pulp grades. Total does not include estimated consumption of newspaper grades for insulation, mailing bags and other end uses.*

[2] *Data excludes wet machine board, construction paper and insulating board.*

[3] *Mountain Region includes Arizona, Idaho, Nevada, New Mexico and Utah.*

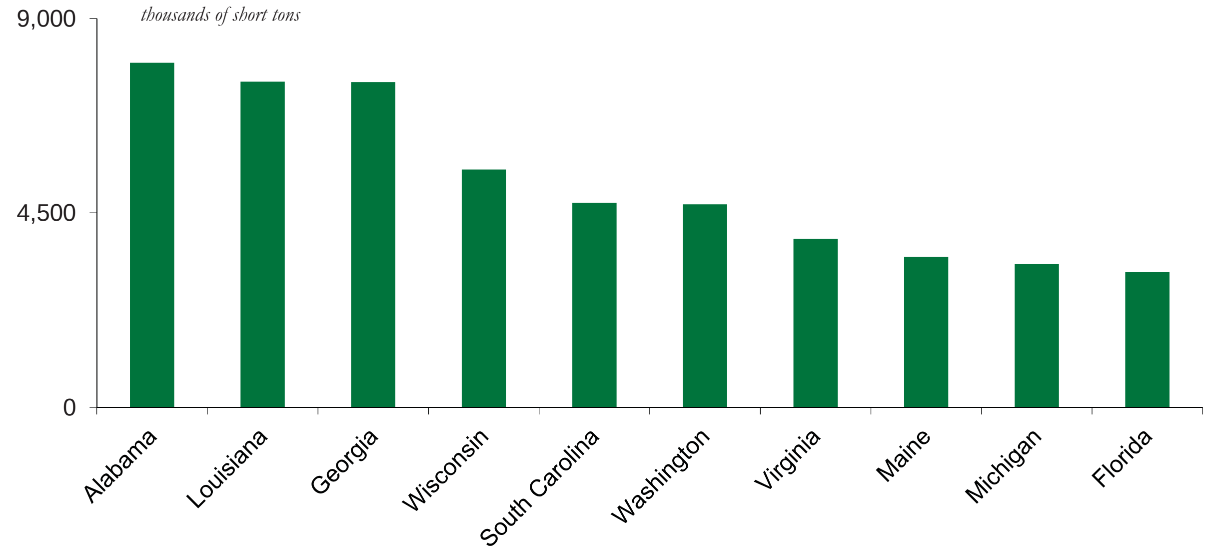
[4] *The following states have production and/or consumption data which have been withheld to avoid disclosure: Iowa, Kansas, Maryland, New Jersey, West Virginia. No data available for the following states: Alaska, Colorado, Delaware, Hawaii, Montana , Nebraska, North Dakota, Rhode Island, South Dakota, Wyoming.*

Top 10 States by Recovered Paper Consumption--2013



Consumption

Top 10 States by Paper & Paperboard Capacity--2013



Capacity

TABLE 8 A United States Annual Capacity to Produce Paper

thousands of short tons

	Paper & Paperboard	Paper	Newsprint	Printing & Writing						
Year	Total	Total	Total	Total	Uncoated Mechanical	Coated Mechanical	Coated Free Sheet	Uncoated Free Sheet	Cotton Fiber	Solid Bleached Bristols
1995	95,749	46,700	7,253	27,495	2,198	4,493	4,876	14,206	189	1,533
1996	98,494	47,167	7,303	27,852	2,306	4,319	5,123	14,488	193	1,423
1997	101,263	48,016	7,442	28,468	2,182	4,513	5,359	14,701	209	1,504
1998	101,833	48,174	7,387	28,794	2,101	4,647	5,391	14,915	211	1,529
1999	102,432	49,020	7,433	29,135	2,028	4,639	5,609	15,222	207	1,430
2000	103,875	49,578	7,464	29,389	1,956	4,849	5,617	15,226	187	1,554
2001	101,886	48,000	7,125	28,016	1,822	4,942	5,411	14,230	172	1,439
2002	100,520	47,079	7,031	27,271	2,010	5,039	5,030	13,620	160	1,412
2003	100,074	47,106	6,940	27,099	1,867	4,975	4,820	13,875	156	1,406
2004	100,038	46,959	6,625	27,274	2,073	4,979	5,017	13,682	120	1,403
2005	99,279	46,194	5,758	27,458	2,242	4,991	5,132	13,558	120	1,415
2006	97,663	45,459	5,526	27,129	2,261	4,674	5,306	13,366	115	1,407
2007	97,052	44,711	5,323	26,651	2,271	4,780	5,295	12,952	108	1,245
2008	96,285	43,329	4,863	25,563	2,373	4,665	5,185	12,095	95	1,150
2009	93,923	41,537	4,819	23,895	2,521	4,182	4,575	11,436	90	1,091
2010	91,045	40,578	4,480	22,675	2,700	3,896	4,433	10,670	91	885
2011	89,778	38,856	3,718	21,653	2,297	3,636	4,346	10,398	83	893
2012	88,315	37,324	3,508	20,566	1,975	3,404	4,333	9,962	80	812
2013	87,349	36,450	3,271	19,689	1,693	3,320	4,189	9,620	39	828

	Packaging & Industrial Converting					Tissue
Year	Total	Unbleached Kraft	Bleached Packaging & Ind. Conv.	Specialty Packaging	Special Industrial	Total
1995	5,400	2,563	511	680	1,646	6,552
1996	5,358	2,409	507	687	1,755	6,654
1997	5,224	2,276	413	839	1,696	6,882
1998	5,114	2,134	398	809	1,773	6,879
1999	5,331	2,135	449	1,049	1,698	7,121
2000	5,277	2,029	375	1,183	1,690	7,448
2001	5,065	1,896	372	1,151	1,646	7,794
2002	4,816	1,786	374	1,091	1,565	7,961
2003	4,976	1,765	380	1,096	1,735	8,091
2004	4,894	1,690	335	1,188	1,681	8,166
2005	4,703	1,653	332	1,154	1,564	8,275
2006	4,565	1,566	204	1,146	1,649	8,239
2007	4,623	1,602	213	1,098	1,710	8,114
2008	4,680	1,676	194	1,141	1,669	8,223
2009	4,488	1,628	204	1,156	1,500	8,335
2010	4,941	1,811	214	1,151	1,765	8,482
2011	4,914	1,805	262	1,142	1,705	8,571
2012	4,843	1,704	253	1,123	1,763	8,407
2013	4,867	1,718	248	1,237	1,664	8,622

Source: AF&PA's Paper, Paperboard and Wood Pulp Capacity Survey.

TABLE 8 B United States Annual Capacity to Produce Paperboard

thousands of short tons

	Paperboard	Boxboard & Other Paperboard							
Year	Total	Total	Unbleached Kraft Folding	Unbleached Other	Solid Bleached Folding	Liquid Packaging & Food Service	Bleached Other[1]	Recycled Ctd & Unctd Board	Gypsum Wall Board Facing
1995	49,049	15,357	1,845	481	2,557	2,354	285	6,371	1,464
1996	51,327	15,674	2,017	476	2,763	2,406	143	6,363	1,506
1997	53,247	16,024	2,073	444	3,032	2,359	149	6,404	1,563
1998	53,659	16,127	2,284	408	3,001	2,393	151	6,305	1,585
1999	53,412	16,790	2,425	510	3,092	2,441	245	6,469	1,608
2000	54,297	16,881	2,413	492	3,061	2,443	227	6,525	1,720
2001	53,886	16,689	2,435	399	3,003	2,488	213	6,380	1,771
2002	53,441	16,619	2,477	346	3,108	2,434	210	6,216	1,828
2003	52,968	22,511	2,446	331	3,219	2,485	143	6,009	1,869
2004	53,079	22,365	2,408	377	3,190	2,580	187	5,860	1,903
2005	53,085	21,916	2,448	319	3,236	2,736	134	5,586	1,871
2006	52,204	21,318	2,522	355	2,977	2,703	130	5,415	1,801
2007	52,341	21,085	2,575	351	3,111	2,729	156	5,225	1,713
2008	52,956	15,949	2,575	377	3,148	2,735	149	5,233	1,732
2009	52,386	20,330	2,500	294	2,976	2,746	141	4,941	1,791
2010	50,467	20,157	2,500	-	2,611	3,009	245	5,061	1,670
2011	50,922	14,919	2,522	-	2,475	3,121	235	5,040	1,526
2012	50,991	19,644	2,549	-	2,399	3,202	188	4,890	1,526
2013	50,900	14,590	2,499	-	2,202	3,250	204	4,866	1,569

	Containerboard					
Year	Total	Unbleached Kraft Liner	Bleached Kraft Liner [1]	Semi-chemical Medium	Recycled Liner	Recycled Medium [2]
1995	33,692	21,363	178	5,994	2,481	3,676
1996	35,653	21,624	209	5,778	3,775	4,267
1997	37,223	22,215	215	5,982	4,489	4,322
1998	37,532	22,254	179	5,955	4,637	4,507
1999	36,622	20,734	180	6,132	5,059	4,517
2000	37,416	20,964	158	6,331	5,291	4,672
2001	37,197	20,533	128	6,409	5,230	4,897
2002	36,822	20,336	126	6,452	5,199	4,709
2003	36,466	20,773	148	6,472	4,615	4,458
2004	36,574	20,927	167	6,710	4,385	4,385
2005	36,755	20,951	84	6,884	4,403	4,433
2006	36,301	21,078	89	6,331	4,332	4,471
2007	36,481	21,288	90	6,200	4,602	4,301
2008	37,007	21,393	87	6,080	5,037	4,410
2009	36,997	21,219	92	6,108	5,132	4,446
2010	35,371	19,808		5,578	5,462	4,523
2011	36,003	20,225		5,588	5,539	4,651
2012	36,237	20,445		5,485	5,364	4,943
2013	36,309	20,400		5,377	5,689	4,843

TABLE 8 C

thousands of short tons

	Construction Paper & Board & Wet Machine Board			
Year	Total	Construction Paper [3]	Wet Machine Board [3]	Insulating Board [3]
1995	2,188	905	117	1,166
1996	2,227	907	117	1,203
1997	2,147	911	108	1,128
1998	2,165	904	117	1,144
1999	2,035	785	84	1,166
2000	1,990	790	77	1,123
2001	1,882	703	66	1,113
2002	1,882	703	66	1,113
2003	1,891	724	66	1,101
2004	1,884	720	62	1,102
2005	1,877	710	63	1,104
2006	1,870	700	64	1,106
2007	1,768	677	60	1,031
2008	1,747	651	65	1,031
2009	1,488	528	64	896
2010	1,317			
2011	1,145			
2012	1,140			
2013	1,082			

[1] *Starting 2010, Bleached Kraft Liner numbers included in Bleached Other Paperboard*

[3] *Starting 2010, Total Capacity for Construction Paper & Board is not broken out by category.*

Wood Pulp Capacity

TABLE 9 A United States Annual Capacity to Produce Wood Pulp *thousands of short tons*

	Wood Pulp for Paper & Board	Dissolving	Chemical Paper Grades					Semi-chemical	Mechanical	Wood Pulp for Construction Paper & Board
Year	Total	Total	Total	SULFITE Total	SULFATE Bleached Hardwood	SULFATE Bleached Softwood	SULFATE Unbleached	Total	Total	Total
1995	68,799	1,435	56,275	1,330	16,940	15,107	22,898	4,269	6,820	622
1996	68,793	1,483	56,198	1,288	16,538	15,439	22,933	4,255	6,857	722
1997	70,319	1,154	57,802	1,291	17,202	15,377	23,932	4,267	7,096	735
1998	69,887	1,100	56,499	1,283	16,931	14,535	23,750	5,281	7,007	726
1999	68,946	1,101	56,179	1,220	17,097	14,956	22,906	4,410	7,256	704
2000	69,931	1,183	57,222	1,230	17,399	14,859	23,734	4,447	7,079	597
2001	68,414	1,155	56,216	943	16,966	14,968	23,339	4,459	6,584	551
2002	68,052	1,175	56,087	855	16,779	14,994	23,459	4,436	6,354	550
2003	67,637	998	55,854	832	16,914	15,069	23,039	4,577	6,208	542
2004	67,547	875	55,956	722	16,811	15,265	23,158	4,496	6,220	543
2005	67,401	876	56,138	654	16,939	15,410	23,135	4,261	6,126	542
2006	66,370	843	55,403	553	16,397	15,194	23,259	4,028	6,096	542
2007	66,442	745	55,502	557	16,230	15,312	23,403	3,949	6,246	542
2008	65,965	752	55,245	519	16,131	15,333	23,262	3,974	5,994	542
2009	65,245	737	54,588	481	15,529	14,985	23,593	3,933	5,987	524
2010	63,503	767	53,057	475	14,978	14,794	22,810	3,657	6,022	442
2011	63,340	894	53,170	474	14,736	14,857	23,103	3,651	5,625	405
2012	63,353	938	53,402	289	14,659	15,086	23,368	3,619	5,394	405
2013	61,864	1,196	51,927	283	13,745	14,902	22,997	3,531	5,210	319

Source: AF&PA's Paper, Paperboard and Wood Pulp Capacity Survey.

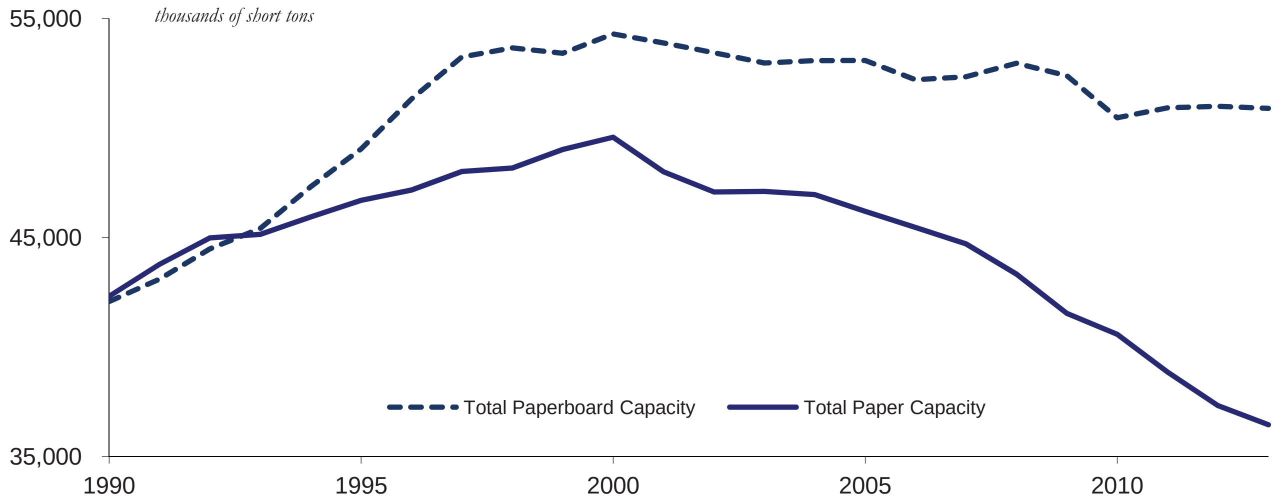
Market Pulp Capacity

TABLE 9 B United States Annual Capacity to Produce Market Pulp *thousands of short tons*

	Market Pulp	Dissolving	Chemical Paper Grades				
Year	Total	Total	Total	SULFITE Total[1]	SULFATE Bleached Hardwood	SULFATE Bleached Softwood	SULFATE Unbleached[1]
1995	11,125	1,435	9,690	187	3,811	5,434	258
1996	10,721	1,483	9,238	175	3,323	5,443	297
1997	10,505	1,154	9,351	177	3,415	5,295	464
1998	10,083	1,100	8,983	75	3,132	5,332	444
1999	9,741	1,101	8,640	113	2,706	5,416	405
2000	10,338	1,183	9,155	113	3,106	5,552	384
2001	10,514	1,155	9,359		3,152	5,776	
2002	10,538	1,175	9,363		3,155	5,757	
2003	10,624	998	9,626		3,291	5,887	
2004	10,455	875	9,580		2,800	6,326	
2005	10,680	876	9,804		2,806	6,441	
2006	10,185	843	9,342		2,369	6,498	
2007	10,442	745	9,697		2,454	6,758	
2008	10,726	752	9,974		2,631	7,118	
2009	10,785	737	10,048		2,572	7,060	
2010	10,617	767	9,850		2,395	7,115	
2011	11,023	894	10,129		2,256	7,520	
2012	11,232	938	10,294		2,310	7,648	
2013	11,028	1,192	9,836		1,878	7,649	

[1] *Starting 2001, Sulfite and Unbleached Sulfate numbers included in Total Chemical Paper Grades*

U.S. Annual Capacity to Produce Paper and Paperboard



U.S. Annual Capacity to Produce Wood Pulp for Paper & Board

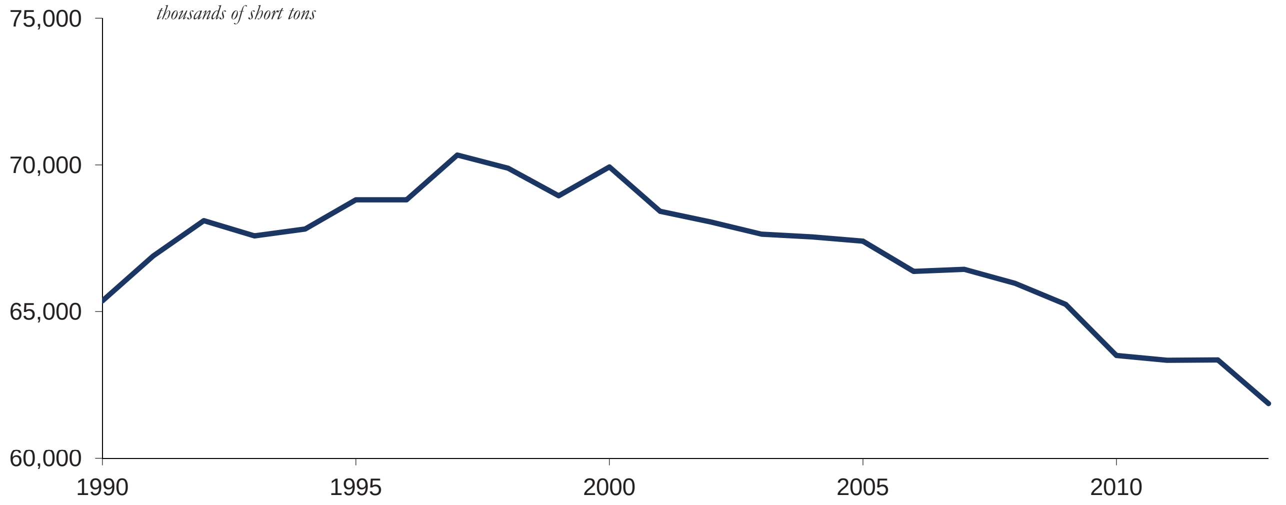


TABLE 10 Imports by Year

value in thousands of dollars

	2011		2012		2013	
	Short Tons	Value	Short Tons	Value	Short Tons	Value
Total Pulp (Wood, Cotton & Other)	**6,170,822**	**3,863,905**	**5,632,328**	**3,201,245**	**6,135,013**	**3,495,198**
Wood Pulp	**6,117,086**	**3,830,369**	**5,599,197**	**3,185,347**	**6,112,163**	**3,485,337**
Dissolving & Special Alpha	273,981	366,413	363,124	369,916	223,990	306,860
Sulfite, Paper Grades, Total	240,164	129,230	237,137	128,680	238,246	119,230
Bl. Sulfite	240,106	129,216	236,612	128,401	237,316	118,759
Unbl. Sulfite	58	14	525	278	930	471
Sulfate, Paper Grades, Total	5,190,068	3,139,769	4,664,181	2,537,460	5,343,868	2,932,971
Bl. Sulfate	5,040,351	3,035,217	4,509,697	2,439,112	5,169,220	2,831,279
Semi Bl. Sulfate	59,233	43,455	49,415	42,134	45,276	41,332
Unbl. Sulfate	90,484	61,098	105,069	56,214	129,372	60,360
Mechanical, Semi-Chemical & Other	412,873	194,956	334,755	149,291	306,059	126,275
Cotton & Other Pulp	**53,736**	**33,536**	**33,131**	**15,898**	**22,850**	**9,861**
Recovered Paper	**1,004,809**	**170,734**	**1,094,024**	**152,882**	**893,931**	**123,247**
Paper, Board & Converted Products	**13,171,363**	**15,343,984**	**12,555,655**	**15,086,882**	**13,128,656**	**15,410,194**
Paper & Paperboard [1]	**11,116,086**	**9,485,317**	**10,489,713**	**9,117,255**	**11,006,645**	**9,318,570**
Paper	9,219,093	7,990,410	8,737,981	7,688,335	9,041,359	7,672,028
Newsprint	2,511,754	1,463,910	2,289,266	1,344,160	2,332,198	1,290,467
Printing Writing & Related	5,482,516	4,507,129	5,190,731	4,298,497	5,415,035	4,344,533
Clay Coated Free Sheet	836,122	763,600	746,781	677,923	747,264	658,435
Clay Coated Mechanical	835,516	709,634	1,032,239	838,942	967,859	775,747
Other Printing Writing & Related	36,129	53,308	32,514	49,573	35,057	53,776
Uncoated Free Sheet [2]	1,009,662	974,395	1,042,531	1,031,020	1,127,682	1,053,832
Uncoated Mechanical	2,765,087	2,006,193	2,336,666	1,701,038	2,537,173	1,802,744
Packaging & Industrial Converting	405,844	492,854	421,148	497,337	434,557	503,443
Bleached Kraft	176,447	231,850	194,214	232,773	184,835	219,862
Other	72,146	115,507	65,588	117,452	74,274	129,441
Unbleached Kraft	157,251	145,496	161,346	147,112	175,448	154,140
Tissue & Sanitary	322,541	379,232	323,829	371,881	328,950	378,249
Special Industrial & Absorbent	496,438	1,147,284	513,007	1,176,459	530,619	1,155,336
Paperboard	1,782,870	1,433,960	1,703,382	1,396,526	1,925,665	1,619,741
Kraft Linerboard (Unbl. & Other)	217,921	174,203	195,783	146,281	258,566	200,766
Other Unbleached Kraft Paperboard	209,401	164,322	214,238	171,308	260,090	224,233
Semi Chemical Paperboard	122,822	56,906	105,435	48,756	129,468	70,189
Bleached Kraft Paperboard	106,638	132,786	115,394	153,205	132,461	180,995
Folding Boxboard	6,462	7,698	8,319	8,435	3,467	4,897
Liquid Pkg. Stock	4,870	15,884	11,164	38,522	16,689	52,013
Other Kraft	30,156	36,121	26,088	30,017	25,815	28,957
Plate, Dish, Cup & Tray	65,150	73,082	69,823	76,231	86,490	95,128
Other Paperboard	1,126,088	905,744	1,072,532	876,977	1,145,080	943,558
Construction Paper & Board	113,845	60,495	48,071	31,958	39,396	26,415
Wet Machine Board	278	451	279	437	225	388
Converted Paper & Board Products	**2,055,277**	**5,858,667**	**2,065,942**	**5,969,626**	**2,122,011**	**6,091,624**
Wallpaper	4,406	44,190	4,596	48,188	4,975	51,172
Printing Writing & Related	168,461	702,344	167,642	715,182	161,722	688,387
Cigarette Paper	35,951	193,193	39,635	208,307	32,593	180,888
Packaging & Industrial Converting	267,189	938,852	271,700	959,698	285,711	958,344
Tissue & Sanitary	686,504	1,798,455	681,069	1,757,860	689,361	1,823,223
Special Industrial, Molded Pulp, Etc.	284,517	687,160	287,796	736,311	292,837	746,990
Boxes, Cartons and Drums	423,798	1,082,686	412,024	1,073,361	422,420	1,127,486
Sanitary Food Ctns and Other Bleached	152,305	358,348	178,366	433,755	194,226	468,976
Corrugated Paper & Board	32,146	53,441	23,114	36,965	38,166	46,159
No Tonnage Figures Available [3]	**--**	**784,486**	**--**	**798,072**	**--**	**788,854**

Source: U.S. Bureau of the Census

[1] *Includes Paper, Paperboard, Wet Machine Board, and Construction Paper and Board.*

[2] *Includes Uncut and Cut-to-Size Uncoated Free Sheet Paper.*

[3] *Value included only in the "Total Imports" Category.*

[4] *Value represents Total Value, not CIF Value.*

TABLE 11 Exports by Year

value in thousands of dollars

	2011		2012		2013	
	Short Tons	Value	Short Tons	Value	Short Tons	Value
Total Pulp (Wood, Cotton & Other)	**9,330,148**	**5,977,677**	**8,395,524**	**5,595,654**	**8,386,428**	**5,589,184**
Wood Pulp	**9,068,200**	**5,719,495**	**8,126,025**	**5,335,973**	**8,146,838**	**5,369,148**
Dissolving & Special Alpha	695,688	816,746	728,677	951,369	816,125	1,016,074
Sulfite, Paper Grades, Total	129,272	73,817	84,836	44,421	64,879	30,257
Bl. Sulfite	115,174	68,686	64,320	36,997	45,802	24,866
Unbl. Sulfite	14,098	5,131	20,516	7,423	19,077	5,391
Sulfate, Paper Grades, Total	7,963,927	4,708,375	7,050,330	4,212,509	7,135,805	4,258,430
Bl. Sulfate	7,059,290	4,356,538	6,349,222	3,878,206	6,519,099	3,945,393
Semi Bl. Sulfate	567,313	200,075	445,608	218,413	374,621	198,056
Unbl. Sulfate	337,324	151,762	255,500	115,889	242,085	114,981
Mechanical, Semi-Chemical & Other	279,313	120,557	262,182	127,674	130,029	64,387
Cotton & Other Pulp	**261,948**	**258,182**	**269,499**	**259,681**	**239,590**	**220,035**
Recovered Paper	**23,179,198**	**3,757,181**	**22,187,777**	**3,382,063**	**20,794,113**	**3,140,183**
Paper, Board & Converted Products	**16,453,471**	**16,242,283**	**15,768,729**	**16,171,773**	**15,693,754**	**16,470,881**
Paper & Paperboard [1]	**13,902,472**	**10,571,571**	**13,125,845**	**10,205,664**	**12,890,893**	**10,172,413**
Paper	4,782,227	4,772,157	4,637,994	4,798,381	4,544,767	4,603,506
Newsprint	930,233	534,631	805,423	453,668	847,672	445,237
Printing Writing & Related	2,495,949	2,487,712	2,576,318	2,558,908	2,504,029	2,396,381
Clay Coated Free Sheet	656,496	661,517	645,238	641,806	620,420	592,147
Clay Coated Mechanical	473,479	344,254	460,442	388,897	376,409	323,156
Other Printing Writing & Related	99,887	98,473	140,765	136,667	167,424	158,237
Uncoated Free Sheet [2]	984,464	1,137,521	1,075,070	1,174,381	1,063,108	1,110,119
Uncoated Mechanical	281,623	245,947	254,803	217,156	276,668	212,722
Packaging & Industrial Converting	780,322	495,912	588,565	469,484	520,516	439,720
Bleached Kraft	97,788	107,084	107,918	108,247	91,526	95,531
Other	57,096	99,704	55,520	87,663	43,125	83,411
Unbleached Kraft	625,438	289,125	425,127	273,573	385,865	260,778
Tissue & Sanitary	134,545	169,195	142,307	176,470	158,623	198,911
Special Industrial & Absorbent	441,178	1,084,707	525,381	1,139,852	513,927	1,123,256
Paperboard	9,048,038	5,744,464	8,409,977	5,355,361	8,296,658	5,531,339
Kraft Linerboard (Unbl. & Other)	4,893,079	2,375,595	4,361,490	2,124,792	4,077,085	2,209,647
Other Unbleached Kraft Paperboard	1,077,406	721,375	1,077,807	680,442	1,185,901	784,767
Semi Chemical Paperboard	400,381	195,078	388,658	180,696	360,575	183,577
Bleached Kraft Paperboard	1,914,623	1,948,232	1,813,638	1,836,170	1,797,109	1,771,129
Folding Boxboard	593,388	590,511	494,375	508,420	545,268	541,248
Liquid Pkg. Stock	561,697	616,543	533,221	591,033	521,221	574,188
Other Kraft	542,483	505,749	555,689	500,635	475,644	415,750
Plate, Dish, Cup & Tray	217,055	235,429	230,353	236,082	254,976	239,944
Other Paperboard	762,549	504,184	768,384	533,261	875,988	582,220
Construction Paper & Board	71,491	54,306	77,419	51,168	48,985	37,187
Wet Machine Board	716	644	455	754	483	382
Converted Paper & Board Products	**2,550,999**	**5,670,712**	**2,642,884**	**5,966,109**	**2,802,861**	**6,298,468**
Wallpaper	8,149	83,038	8,041	84,572	8,174	89,407
Printing Writing & Related	154,361	700,484	146,734	724,152	156,123	765,178
Cigarette Paper	11,249	39,915	8,551	40,871	6,251	34,352
Packaging & Industrial Converting	389,320	951,967	433,362	977,497	466,625	1,023,064
Tissue & Sanitary	547,526	1,632,035	586,901	1,767,512	609,065	1,833,663
Special Industrial, Molded Pulp, Etc.	55,022	150,430	58,124	160,545	56,177	159,309
Boxes, Cartons and Drums	868,978	1,400,216	807,717	1,414,281	822,779	1,493,456
Sanitary Food Ctns and Other Bleached	190,330	412,583	204,341	443,944	211,997	454,123
Corrugated Paper & Board	326,064	300,044	389,113	352,734	465,670	445,917
No Tonnage Figures Available [3]	**--**	**229,186**	**--**	**192,391**	**--**	**200,117**

Source: U.S. Bureau of the Census

[1] *Includes Paper, Paperboard, Wet Machine Board, and Construction Paper and Board.*

[2] *Includes Uncut and Cut-to-Size Uncoated Free Sheet Paper.*

[3] *Value included only in the "Total Exports" Category.*

[4] *Value represents Total Value, not CIF Value.*

TABLE 12 Imports by Region for 2013

	World		Canada	
	Short Tons	Value	Short Tons	Value
Total Pulp (Wood, Cotton & Other)	**6,135,013**	**3,495,198**	**3,707,322**	**2,220,908**
Wood Pulp	**6,112,163**	**3,485,337**	**3,697,108**	**2,219,559**
Dissolving & Special Alpha	223,990	306,860	126,373	150,442
Sulfite, Paper Grades, Total	238,246	119,230	234,127	116,884
Bl. Sulfite	237,316	118,759	233,207	116,415
Unbl. Sulfite	930	471	920	469
Sulfate, Paper Grades, Total	5,343,868	2,932,971	3,061,500	1,834,340
Bl. Sulfate	5,169,220	2,831,279	2,957,423	1,766,807
Semi Bl. Sulfate	45,276	41,332	37,125	29,517
Unbl. Sulfate	129,372	60,360	66,952	38,016
Mechanical, Semi-Chemical & Other	306,059	126,275	275,108	117,893
Cotton & Other Pulp	**22,850**	**9,861**	**10,214**	**1,349**
Recovered Paper	**893,931**	**123,247**	**799,590**	**107,633**
Paper, Board & Converted Products	**13,128,656**	**15,410,194**	**7,768,636**	**7,225,184**
Paper & Paperboard [1]	**11,006,645**	**9,318,570**	**6,887,363**	**5,009,035**
Paper	9,041,359	7,672,028	5,612,780	4,018,755
Newsprint	2,332,198	1,290,467	2,323,584	1,286,091
Printing Writing & Related	5,415,035	4,344,533	2,824,160	2,168,618
Clay Coated Free Sheet	747,264	658,435	3,074	4,204
Clay Coated Mechanical	967,859	775,747	376,787	306,654
Other Printing Writing & Related	35,057	53,776	22,382	23,451
Uncoated Free Sheet [2]	1,127,682	1,053,832	347,246	337,322
Uncoated Mechanical	2,537,173	1,802,744	2,074,671	1,496,986
Packaging & Industrial Converting	434,557	503,443	225,098	232,573
Bleached Kraft	184,835	219,862	110,688	125,691
Other	74,274	129,441	2,925	5,044
Unbleached Kraft	175,448	154,140	111,485	101,838
Tissue & Sanitary	328,950	378,249	123,068	158,450
Special Industrial & Absorbent	530,619	1,155,336	116,870	173,023
Paperboard	1,925,665	1,619,741	1,236,204	965,197
Kraft Linerboard (Unbl. & Other)	258,566	200,766	231,472	184,434
Other Unbleached Kraft Paperboard	260,090	224,233	29,532	15,282
Semi Chemical Paperboard	129,468	70,189	95,740	49,141
Bleached Kraft Paperboard	132,461	180,995	85,358	92,215
Folding Boxboard	3,467	4,897	1,644	1,367
Milk Carton Stock	16,689	52,013	64	76
Other Kraft	25,815	28,957	733	734
Plate, Dish, Cup & Tray	86,490	95,128	82,917	90,038
Other Paperboard	1,145,080	943,558	794,102	624,125
Construction Paper & Board	39,396	26,415	38,301	24,950
Wet Machine Board	225	388	78	133
Converted Paper & Board Products	**2,122,011**	**6,091,624**	**881,273**	**2,216,149**
Wallpaper	4,975	51,172	1,150	7,213
Printing Writing & Related	161,722	688,387	22,036	143,168
Cigarette Paper	32,593	180,888	3,536	28,476
Packaging & Industrial Converting	285,711	958,344	74,403	252,703
Tissue & Sanitary	689,361	1,823,223	337,783	981,444
Special Industrial, Molded Pulp, Etc.	292,837	746,990	143,862	181,368
Boxes, Cartons and Drums	422,420	1,127,486	190,796	401,979
Sanitary Food Ctns and Other Bleached	194,226	468,976	97,933	207,961
Corrugated Paper & Board	38,166	46,159	9,774	11,836
No Tonnage Figures Available [3]	**--**	**788,854**	**--**	**23,771**

Source: U.S. Bureau of the Census

[1] *Includes Paper, Paperboard, Wet Machine Board, and Construction Paper and Board.*

[2] *Includes Uncut and Cut-to-Size Uncoated Free Sheet Paper.*

[3] *Value included only in the "Total Imports" Category.*

[4] *Value represents Total Value, not CIF Value.*

Imports by Region 2013 (Cont.)

value in thousands of dollars

Europe		Asia		Mexico & South America		Other	
Short Tons	Value	Short Tons	Value	Short Tons	Value	Short Tons	Value
57,896	**42,598**	**17,637**	**16,528**	**2,352,158**	**1,186,941**	**0**	**28,223**
55,441	**39,929**	**7,456**	**10,685**	**2,352,158**	**1,186,941**	**0**	**28,223**
10,507	11,511	0	0	87,110	116,685	0	28,223
3,954	2,298	165	48	0	0	0	0
3,954	2,298	155	46	-	-	0	0
0	0	10	2	0	0	-	-
40,399	25,747	7,030	10,590	2,234,939	1,062,294	0	0
33,553	21,292	2,396	1,261	2,175,848	1,041,919	0	0
1,951	1,602	4,634	9,329	1,566	883	-	-
4,895	2,852	0	0	57,525	19,492	0	0
581	373	261	47	30,109	7,962	-	-
2,455	**2,669**	**10,181**	**5,843**	**0**	**0**	**0**	**0**
828	**328**	**4,580**	**2,285**	**88,933**	**13,002**	**0**	**0**
2,368,716	**2,998,399**	**2,065,394**	**3,805,487**	**751,408**	**1,262,771**	**174,502**	**118,352**
2,236,721	**2,302,840**	**1,272,494**	**1,443,421**	**443,841**	**455,254**	**166,226**	**108,021**
1,838,844	1,913,927	1,128,749	1,308,960	378,842	371,276	82,144	59,109
8,583	4,356	31	21	0	0	0	0
1,538,861	1,284,103	764,949	645,432	229,035	204,150	58,030	42,230
380,955	366,035	362,558	287,516	677	679	0	0
471,258	369,679	118,912	97,848	826	1,518	76	47
2,614	3,756	9,903	26,392	0	0	158	177
239,390	265,032	256,099	208,381	227,174	201,178	57,773	41,918
444,644	279,601	17,477	25,294	358	774	23	89
130,274	190,693	15,200	28,180	59,813	49,337	4,172	2,660
59,892	69,810	14,254	24,356	1	4	0	0
51,381	96,475	474	2,555	19,494	25,367	0	0
19,001	24,409	472	1,269	40,318	23,965	4,172	2,660
28,387	35,665	115,073	121,766	61,807	61,719	615	649
132,739	399,111	233,496	513,563	28,187	56,070	19,327	13,570
397,311	388,024	143,071	133,652	64,997	83,956	84,082	48,911
4,668	3,437	3,703	1,535	299	191	18,424	11,168
170,597	173,374	868	2,197	1,765	1,745	57,328	31,635
32,022	20,343	1,706	706	0	0	0	0
17,786	29,944	3,576	6,524	25,733	52,297	8	15
688	803	1,055	2,650	80	77	-	-
3,563	9,076	389	1,132	12,673	41,730	-	-
10,114	15,377	2,011	2,475	12,949	10,356	8	15
3,421	4,689	121	267	31	134	0	0
172,238	160,927	133,218	122,690	37,200	29,723	8,322	6,093
436	667	657	776	2	22	-	-
130	222	17	32	0	0	-	-
131,995	**695,559**	**792,900**	**2,362,067**	**307,567**	**807,518**	**8,276**	**10,332**
2,176	23,009	1,630	20,795	1	8	18	147
21,566	89,598	69,595	282,150	48,488	172,470	37	1,002
21,700	121,086	1,281	13,805	6,076	17,521	0	0
21,934	94,413	142,276	512,581	45,922	95,401	1,176	3,247
15,752	67,162	253,303	516,790	82,286	257,168	237	659
22,997	192,996	71,278	274,490	54,650	97,846	50	290
15,289	63,783	166,659	537,468	49,579	123,785	97	472
4,650	25,284	72,598	194,746	18,749	39,736	296	1,250
5,931	18,228	14,280	9,243	1,816	3,584	6,365	3,267
--	**44,686**	**--**	**555,129**	**--**	**144,162**	**--**	**21,105**

TABLE 13 Exports by Region for 2013

	World		Canada	
	Short Tons	Value	Short Tons	Value
Total Pulp (Wood, Cotton & Other)	**8,386,428**	**5,589,184**	**229,304**	**142,108**
Wood Pulp	**8,146,838**	**5,369,148**	**189,658**	**116,645**
Dissolving & Special Alpha	816,125	1,016,074	99	139
Sulfite, Paper Grades, Total	64,879	30,257	23,808	9,582
Bl. Sulfite	45,802	24,866	12,982	7,089
Unbl. Sulfite	19,077	5,391	10,826	2,493
Sulfate, Paper Grades, Total	7,135,805	4,258,430	161,876	105,295
Bl. Sulfate	6,519,099	3,945,393	159,028	103,702
Semi Bl. Sulfate	374,621	198,056	2,673	1,483
Unbl. Sulfate	242,085	114,981	175	110
Mechanical, Semi-Chemical & Other	130,029	64,387	3,875	1,629
Cotton & Other Pulp	**239,590**	**220,035**	**39,646**	**25,462**
Recovered Paper	**20,794,113**	**3,140,183**	**696,757**	**107,562**
Paper, Board & Converted Products	**15,693,754**	**16,470,881**	**4,049,659**	**5,426,417**
Paper & Paperboard [1]	**12,890,893**	**10,172,413**	**2,770,919**	**2,518,587**
Paper	4,544,767	4,603,506	1,418,473	1,599,551
Newsprint	847,672	445,237	102,105	60,595
Printing Writing & Related	2,504,029	2,396,381	751,158	870,780
Clay Coated Free Sheet	620,420	592,147	329,433	340,957
Clay Coated Mechanical	376,409	323,156	92,792	93,931
Other Printing Writing & Related	167,424	158,237	4,787	10,222
Uncoated Free Sheet [2]	1,063,108	1,110,119	297,753	398,979
Uncoated Mechanical	276,668	212,722	26,393	26,691
Packaging & Industrial Converting	520,516	439,720	194,987	155,416
Bleached Kraft	91,526	95,531	40,143	42,294
Other	43,125	83,411	6,435	13,023
Unbleached Kraft	385,865	260,778	148,409	100,098
Tissue & Sanitary	158,623	198,911	84,993	100,872
Special Industrial & Absorbent	513,927	1,123,256	285,230	411,889
Paperboard	8,296,658	5,531,339	1,327,960	904,222
Kraft Linerboard (Unbl. & Other)	4,077,085	2,209,647	279,085	162,362
Other Unbleached Kraft Paperboard	1,185,901	784,767	224,218	152,517
Semi Chemical Paperboard	360,575	183,577	36,573	17,912
Bleached Kraft Paperboard	1,797,109	1,771,129	191,663	165,759
Folding Boxboard	545,268	541,248	66,978	62,710
Liquid Pkg. Stock	521,221	574,188	2,320	2,736
Other Kraft	475,644	415,750	101,520	82,871
Plate, Dish, Cup & Tray	254,976	239,944	20,845	17,442
Other Paperboard	875,988	582,220	596,421	405,672
Construction Paper & Board	48,985	37,187	24,486	14,814
Wet Machine Board	483	382	-	-
Converted Paper & Board Products	**2,802,861**	**6,298,468**	**1,278,740**	**2,907,829**
Wallpaper	8,174	89,407	1,592	12,994
Printing Writing & Related	156,123	765,178	42,492	205,571
Cigarette Paper	6,251	34,352	3,733	14,016
Packaging & Industrial Converting	466,625	1,023,064	234,553	389,144
Tissue & Sanitary	609,065	1,833,663	428,255	1,320,130
Special Industrial, Molded Pulp, Etc.	56,177	159,309	22,220	50,988
Boxes, Cartons and Drums	822,779	1,493,456	297,094	510,454
Sanitary Food Ctns and Other Bleached	211,997	454,123	123,012	274,476
Corrugated Paper & Board	465,670	445,917	125,789	130,056
No Tonnage Figures Available [3]	**--**	**200,117**	**--**	**80,777**

Source: U.S. Bureau of the Census

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[1] Includes Paper, Paperboard, Wet Machine Board, and Construction Paper and Board.

[2] Includes Uncut and Cut-to-Size Uncoated Free Sheet Paper.

[3] Value included only in the "Total Exports" Category.

[4] Value represents Total Value, not CIF Value.

Exports by Region 2013 (Cont.)

value in thousands of dollars

Europe		Asia		Mexico & South America		Other	
Short Tons	Value	Short Tons	Value	Short Tons	Value	Short Tons	Value
2,291,763	**1,490,440**	**4,253,767**	**2,905,396**	**1,232,084**	**817,633**	**379,510**	**233,607**
2,229,817	**1,414,120**	**4,163,222**	**2,822,270**	**1,200,665**	**795,155**	**363,476**	**220,958**
107,239	157,195	661,693	780,952	46,962	77,699	132	88
19,146	9,556	12,473	6,312	6,622	3,607	2,830	1,199
15,535	8,527	10,380	5,613	5,024	2,658	1,881	979
3,611	1,030	2,093	700	1,598	949	949	220
2,091,369	1,242,528	3,396,777	1,986,564	1,131,967	706,884	353,816	217,159
2,066,975	1,230,721	2,986,921	1,778,968	954,000	615,712	352,175	216,290
22,622	11,402	171,375	94,092	176,678	90,401	1,273	677
1,772	405	238,481	113,505	1,289	770	368	192
12,063	4,841	92,279	48,441	15,114	6,964	6,698	2,512
61,946	**76,320**	**90,545**	**83,126**	**31,419**	**22,478**	**16,034**	**12,649**
321,790	**81,543**	**18,224,691**	**2,641,021**	**1,535,981**	**305,991**	**14,894**	**4,066**
2,008,757	**1,862,039**	**3,186,348**	**2,943,036**	**5,908,455**	**5,760,488**	**540,535**	**478,902**
1,909,255	**1,438,701**	**3,040,192**	**2,442,109**	**4,668,512**	**3,399,339**	**502,015**	**373,677**
471,149	531,541	1,006,951	876,728	1,482,902	1,445,959	165,292	149,727
5,092	2,320	428,384	209,088	290,733	160,119	21,358	13,115
365,022	292,098	345,400	272,199	927,470	867,049	114,979	94,256
18,583	19,051	86,700	68,949	149,973	130,842	35,731	32,348
94,539	74,843	89,232	72,001	79,599	65,743	20,247	16,639
7,526	5,948	7,611	6,886	145,891	133,788	1,609	1,393
222,756	177,902	55,867	62,075	432,494	429,339	54,238	41,823
21,618	14,354	105,990	62,288	119,513	107,336	3,154	2,053
31,020	32,688	145,705	117,858	129,152	118,646	19,652	15,112
8,440	10,806	22,845	20,935	19,653	20,846	445	649
2,570	5,866	14,455	30,613	19,381	33,139	284	770
20,010	16,016	108,405	66,310	90,118	64,661	18,923	13,692
5,699	10,163	9,622	15,023	55,800	69,825	2,509	3,028
64,316	194,271	77,840	262,559	79,747	230,319	6,794	24,217
1,434,797	904,331	2,029,121	1,561,217	3,169,499	1,938,814	335,281	222,755
853,836	446,012	901,701	469,692	1,825,349	1,017,929	217,114	113,651
305,124	208,716	200,328	140,713	425,861	256,580	30,370	26,241
407	258	5,170	2,208	311,035	159,809	7,390	3,389
244,705	233,389	898,310	932,922	385,240	363,434	77,191	75,626
78,253	83,713	247,004	246,002	120,565	113,144	32,468	35,678
21,654	25,550	405,047	463,082	80,010	71,381	12,190	11,439
48,806	28,190	178,211	164,747	132,364	125,037	14,743	14,905
95,992	95,937	68,048	59,091	52,301	53,872	17,790	13,603
30,725	15,956	23,612	15,682	222,014	141,061	3,216	3,848
3,039	2,555	3,907	4,057	16,111	14,567	1,442	1,194
270	274	213	107	0	0	0	0
99,502	**423,337**	**146,156**	**500,927**	**1,239,943**	**2,361,148**	**38,520**	**105,226**
1,876	22,508	3,647	45,155	830	6,798	229	1,951
11,453	89,253	31,823	130,002	68,096	327,725	2,259	12,627
402	2,456	30	212	1,478	10,445	608	7,223
25,812	92,481	35,169	109,446	156,697	400,023	14,394	31,971
31,639	113,448	48,495	132,061	86,046	232,192	14,630	35,832
4,390	16,884	4,780	20,427	23,387	66,789	1,400	4,221
10,485	46,828	7,568	25,893	506,555	907,092	1,077	3,189
12,060	33,925	9,806	23,709	63,743	114,635	3,376	7,377
1,385	5,553	4,838	14,023	333,111	295,450	547	834
--	**29,166**	**--**	**25,404**	**--**	**58,910**	**--**	**5,860**

TABLE 14 Substitute Import/Export Figures for Specified Grades *thousands of short tons*

	Imports		Exports			
Year	Newsprint [1]	Uncoated Mechanical Paper [2]	Unbleached Kraft Paperboard [3]	Semichemical Paperboard [3]	Bleached Paperboard [3]	Recycled Paperboard [3]
1960	5,426	40	381	31	23	46
1965	6,349	98	905	55	47	32
1970	6,477	233	1,683	84	114	17
1975	5,522	264	1,058	115	256	24
1980	6,880	688	2,380	322	550	83
1985	7,635	1,476	1,830	189	466	26
1990	7,261	1,982	2,691	143	761	49
1995	6,493	3,041	3,297	138	1,022	123
1997	6,360	2,964	5,111	267	1,177	159
1998	6,432	3,083	4,269	229	1,122	168
1999	6,660	3,384	3,737	299	1,124	260
2000	6,537	3,873	3,366	263	1,084	221
2001	5,875	3,911	2,958	313	1,118	281
2002	6,121	4,021	3,132	316	1,153	300
2003	6,047	4,350	3,472	134	1,214	135
2004	5,839	4,457	3,390	156	1,328	107
2005	5,451	4,522	3,549	175	1,335	110
2006	4,910	3,884	3,752	202	1,333	98
2007	4,195	4,357	3,868	298	1,456	83
2008	3,621	4,019	3,919	380	1,495	189
2009	2,557	-	3,951	355	1,403	167
2010	2,417	-	4,012	488	1,548	210
2011	2,233	-	4,151	406	1,484	186
2012 R	2,073	-	4,212	398	1,504	254
2013	2,046	-	4,332	387	1,567	248

Note: The U.S. Import and Export shipment data in this table is obtained from sources other than the U.S. Bureau of the Census. For the grades shown here, Import/Export data from these alternative sources is often used in place of U.S. Census data.

Sources:

[1] *Newsprint - Canadian Shipments to U.S., PPPC; Imports from other countries, U.S. Bureau of the Census;*

[2] *Uncoated Mechanical - Canadian Shipments to U.S. prior to 2009, PPPC; Imports from other countries, U.S. Bureau of the Census.; In 2009, AF&PA began using U.S. Census data for Printing & Writing imports from all countries;*

[3] *Paperboard Grades - 1960 - 1968, U.S. Bureau of the Census; 1968 - present, AF&PA.*

R - Revised

TABLE 15 U.S. Production of Wood Pulp and Market Wood Pulp *thousands of short tons*

	2007	2008	2009	2010	2011	2012	2013
WOOD PULP, TOTAL[1]	58,932	56,745	52,122	54,343	55,125	55,475	54,466
Total Sulfite	431	373	296	326	327	244	237
Total Sulfate	50,194	48,360	45,155	46,808	47,568	47,919	47,206
Bl. & Semi-Bl.	28,791	27,990	25,622	26,470	26,592	26,797	26,038
Unbl. Sulfate	21,403	20,370	19,533	20,338	20,976	21,122	21,168
Total Groundwood	4,759	4,711	3,620	4,088	4,109	4,076	3,898
Stone and Refiner	1,366	1,324	1,020	1,185	1,124	1,163	1,145
Thermo-mechanical	3,393	3,388	2,600	2,904	2,984	2,912	2,753
Semichemical	3,547	3,301	3,051	3,121	3,122	3,237	3,126
MARKET WOOD PULP, TOTAL	9,074	8,642	8,736	8,769	8,998	9,251	9,004
Chemical Total	9,074	8,642	8,736	8,769	8,998	9,251	9,004
Bl. & Semi-Bl. Softwood Sulfate	6,374	6,442	6,439	6,441	6,627	6,881	7,082
Bl. & Semi-Bl. Hardwood Sulfate	2,297	2,031	1,977	2,067	2,091	2,067	1,653
Other[2]	403	169	320	261	280	304	269

Source: AF&PA's Monthly Summary of Pulp Production, Shipments and Inventory.

[1] *Excludes Dissolving & Special Alpha Pulp and Wood Pulp for Construction Paper & Board.*

[2] *Includes Sulfite and Unbleached Sulfate.*

TABLE 16 Fiber Sources for Paper & Paperboard Manufacture *thousands of short tons*

	2007	2008	2009	2010	2011	2012	2013
TOTAL FIBER	92,979	89,400	80,038	84,558	83,852	83,079	83,421
Total Wood Pulp	58,605	56,565	50,598	52,832	53,175	53,001	53,099
Manufactured On-site	49,817	48,362	43,449	45,369	46,009	46,040	45,895
Purchased[1]	7,629	7,087	6,102	6,295	6,034	5,801	6,013
Transferred[1]	1,159	1,116	1,047	1,168	1,132	1,160	1,191
Total Recovered Paper[2]	34,174	32,655	29,268	31,552	30,508	29,913	30,143
Mixed Papers	4,481	4,564	4,150	4,371	3,950	4,204	3,998
Newspapers	5,272	4,850	3,826	3,886	3,441	2,877	2,468
Corrugated	20,159	19,161	17,415	19,327	19,339	19,057	19,805
Pulp Substitutes	1,487	1,359	1,218	1,260	1,204	1,171	1,166
High Grade Deinking	2,775	2,721	2,659	2,708	2,574	2,604	2,706
Other Fibers	200	180	172	174	169	165	179

[1] *Comprises all Dried, Wet Lap or Slush Pulp not produced on-site including transfers from company or affiliated mills.*

[2] *Includes Fiber consumed for construction grades and molded pulp products. Totals not adjusted for differences in rounding.*

Source: AF&PA's Annual Survey of Capacity and Fiber Consumption.

TABLE 17 Pulpwood Consumed in Wood Pulp Manufacture *thousands of cords*

	2007	2008	2009	2010	2011	2012	2013
TOTAL PULPWOOD	100,617	98,035	89,669	93,689	95,507	96,270	95,499
Total Softwood	70,730	69,424	64,476	67,573	69,172	70,047	69,617
Total Hardwood	29,887	28,611	25,193	26,116	26,335	26,223	25,882
Roundwood	53,058	53,630	51,144	53,326	54,216	55,629	54,416
Softwood	36,585	37,573	36,783	38,092	38,937	40,613	39,828
Hardwood	16,473	16,057	14,361	15,234	15,279	15,016	14,588
Roundwood Chips	33,864	33,587	29,118	31,291	32,339	31,221	33,349
Softwood	22,749	22,953	19,829	21,936	22,714	21,633	23,416
Hardwood	11,115	10,634	9,289	9,355	9,625	9,588	9,933
Forest Residues	1,121	789	866	635	634	576	526
Softwood	829	554	604	371	382	340	277
Hardwood	292	235	262	264	252	236	249
Manufacturing Residues	12,574	10,029	8,541	8,437	8,318	8,844	7,208
Softwood	10,567	8,344	7,260	7,174	7,139	7,461	6,096
Hardwood	2,007	1,685	1,281	1,263	1,179	1,383	1,112

Source: AF&PA's Annual Survey of Capacity and Fiber Consumption.

Totals not adjusted for differences in rounding.

TABLE 18 Recovered Paper Utilization in the U.S. [1]

thousands of short tons

Year	Newsprint	Tissue	Kraft Board	Semichemical Board	Recycled Board	All Other	Net Export	Total Recovered Paper	Recovery Rate [2]
1995	3,170	3,396	4,325	1,860	14,363	5,667	9,410	42,189	44.0%
1996	3,164	3,658	4,190	2,004	16,846	5,606	7,611	43,076	45.6%
1997	3,556	3,748	4,269	2,276	17,278	5,673	7,190	43,988	44.2%
1998	3,990	3,809	4,103	2,062	17,820	5,686	7,606	45,076	44.6%
1999	3,704	3,927	4,220	2,019	18,926	5,931	8,091	46,818	44.5%
2000	4,006	4,014	3,840	2,131	18,104	5,552	9,664	47,311	46.0%
2001	3,745	4,224	3,934	2,400	16,823	5,601	10,269	46,996	48.3%
2002	3,597	4,212	3,897	2,527	16,966	5,580	10,867	47,645	48.2%
2003	3,330	4,061	4,430	2,928	15,732	5,369	13,406	49,255	50.3%
2004	3,502	4,276	4,435	3,269	16,433	4,921	13,351	50,187	49.3%
2005	3,504	4,187	4,423	3,044	16,110	4,682	15,323	51,273	51.5%
2006	3,515	4,234	4,705	3,108	15,985	4,749	17,018	53,314	53.0%
2007	3,222	4,290	4,744	2,874	15,879	4,194	19,122	54,325	56.0%
2008	3,018	4,082	4,243	2,974	15,225	3,601	18,680	51,822	57.7%
2009	2,222	3,983	3,838	2,462	14,120	2,724	20,686	50,036	63.6%
2010	2,225	4,106	4,143	2,361	15,820	2,982	19,908	51,545	63.0%
2011	1,836	4,084	3,751	2,399	15,889	2,634	22,174	52,767	66.4%
2012	1,415	4,298	3,393	2,429	15,949	2,514	21,094	51,092	65.1%
2013	1,063	4,417	3,522	2,491	16,261	2,474	19,900	50,128	63.5%

[1] *Data is sourced from www.paperrecycles.org and AF&PA's Annual Recovered Paper Utilization Report.*

[2] *Recovery Rate is the ratio of Recovered Paper collected to New Supply of Paper and Paperboard. Total Recovered Paper is the sum of Recovered Paper Consumption at Paper and Board Mills, Other Uses and Exports less Imports. AF&PA's Recovery Rate is calculated each Spring using preliminary data.*

U.S. Recovered Paper Consumption and Recovery Rate

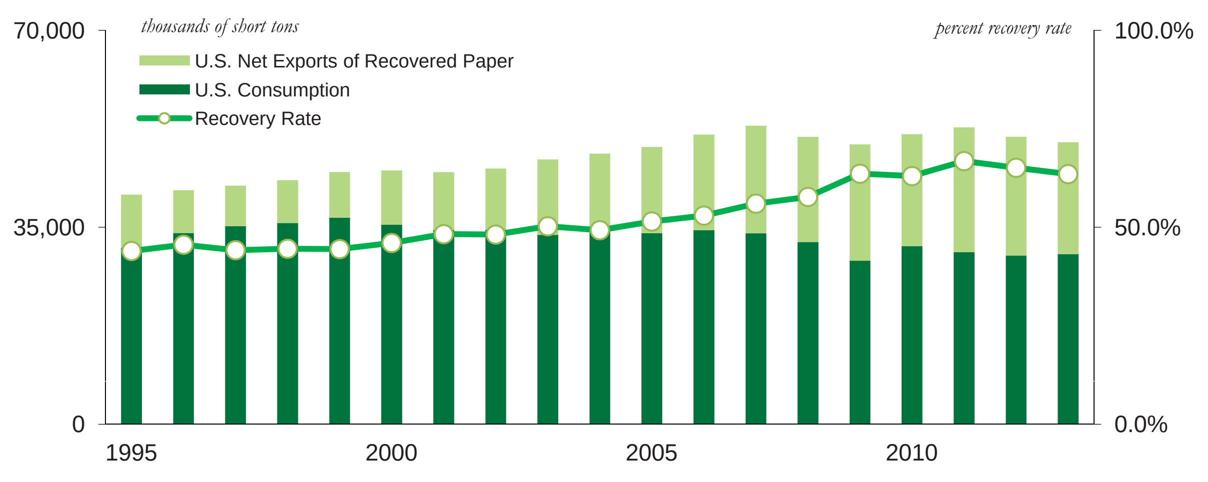


TABLE 19 State Employment Data for the Paper Manufacturing Industry [1]

thousands

	2005	2006	2007	2008	2009	2010 R	2011
Northeast	**85.0**	**77.1**	**78.9**	**75.1**	**67.5**	**62.9**	**61.7**
New England	**30.0**	**26.1**	**26.2**	**23.6**	**21.5**	**18.3**	**17.7**
Maine	8.0	7.7	7.2	7.8	7.8	6.7	6.8
New Hampshire	2.0	1.4	1.5	-	-	-	-
Vermont	1.0	-	-	-	-	-	-
Massachusetts	13.0	11.2	11.6	10.5	9.1	8.2	7.6
Rhode Island	1.0	1.4	1.3	1.2	1.0	-	-
Connecticut	5.0	4.5	4.5	4.0	3.7	3.4	3.3
Middle Atlantic	**55.0**	**51.0**	**52.7**	**51.5**	**46.0**	**44.5**	**44.0**
New York	17.0	15.1	16.9	15.9	14.3	14.1	14.0
New Jersey	14.0	12.0	11.6	11.8	9.8	8.9	8.7
Pennsylvania	24.0	24.0	24.2	23.8	21.9	21.6	21.4
North Central	**131.0**	**127.5**	**128.8**	**124.8**	**113.5**	**111.9**	**110.3**
East North Central	**102.0**	**99.1**	**98.4**	**94.7**	**86.1**	**85.7**	84.7
Ohio	23.0	22.8	22.7	21.8	19.3	18.7	18.7
Indiana	11.0	11.0	11.6	11.0	10.6	10.3	9.9
Illinois	22.0	20.8	18.9	18.4	16.5	16.2	14.7
Michigan	13.0	12.5	12.9	12.5	11.4	10.9	10.8
Wisconsin	33.0	32.0	32.3	31.0	28.4	29.6	30.5
West North Central	**29.0**	**28.4**	**30.4**	**30.1**	**27.3**	**26.2**	**25.6**
Minnesota	12.0	11.3	12.4	12.4	11.6	11.3	11.3
Iowa	4.0	3.6	4.4	4.5	3.6	3.5	3.3
Missouri	9.0	9.4	9.6	9.2	8.8	8.2	8.0
Nebraska	2.0	1.6	1.4	1.5	1.4	1.5	1.5
Kansas	2.0	2.5	2.5	2.5	2.0	1.8	1.6
South	**161.0**	**153.2**	**151.8**	**147.0**	**133.1**	**129.4**	**127.8**
South Atlantic	**77.0**	**72.6**	**72.9**	**70.4**	**63.7**	**62.0**	**61.6**
Delaware	1.0	-	-	-	-	-	-
Maryland	6.0	5.1	4.5	4.2	3.6	3.4	3.0
Virginia	11.0	10.4	9.9	8.9	8.3	7.9	6.9
North Carolina	18.0	16.9	17.8	17.1	15.0	14.6	15.7
South Carolina	12.0	11.7	12.2	11.5	11.5	11.3	11.3
Georgia	20.0	19.3	19.4	19.8	17.5	17.2	17.2
Florida	9.0	9.2	8.9	8.9	7.7	7.6	7.4
East South Central	**43.0**	**40.8**	**40.9**	**40.6**	**36.4**	**35.2**	**34.7**
Kentucky	10.0	9.3	9.6	9.4	8.9	8.7	9.0
Tennessee	15.0	13.6	13.7	13.8	11.6	11.4	10.8
Alabama	13.0	12.5	12.7	12.5	11.7	11.2	11.3
Mississippi	5.0	5.4	4.8	4.9	4.3	3.8	3.6
West South Central	**41.0**	**39.9**	**38.0**	**36.0**	**33.0**	**32.2**	**31.6**
Arkansas	11.0	10.2	8.8	8.6	8.4	8.6	7.7
Louisiana	9.0	8.0	8.5	7.8	6.9	6.6	6.7
Oklahoma	4.0	3.7	4.4	3.9	3.4	3.3	3.3
Texas	17.0	17.9	16.3	15.7	14.3	13.6	14.0
West	**51.0**	**50.1**	**52.6**	**51.0**	**42.9**	**42.7**	**42.1**
Mountain	**10.0**	**9.2**	**10.0**	**9.5**	**6.8**	**8.0**	**8.1**
Idaho	2.0	1.9	1.9	1.8	1.7	1.7	1.7
Colorado	2.0	1.9	2.6	2.6	1.4	1.4	1.3
Arizona	3.0	2.7	2.8	2.7	2.3	2.0	2.0
Utah	3.0	2.7	2.6	2.5	1.4	1.8	2.0
Nevada	-	-	-	-	-	1.0	1.1
Pacific	**41.0**	**40.9**	**42.6**	**41.5**	**36.2**	**34.7**	**34.0**
Washington	11.0	11.9	11.4	10.7	9.4	9.2	9.0
Oregon	6.0	6.1	6.3	6.3	4.9	4.3	4.1
California	24.0	22.9	24.9	24.5	21.9	21.2	20.8
TOTAL REPORTED	**428.0**	**407.9**	**412.1**	**397.9**	**357.0**	**346.9**	**341.9**
TOTAL U.S.A.	**430.0**	**413.4**	**417.1**	**403.7**	**362.6**	**351.4**	**346.5**

Source: U.S. Bureau of the Census: Annual Survey of Manufactures, Geographic Area Statistics.
States not shown have no current or historic data. Data for 2012-13 not available at time of publication.
[1] NAICS Code 322. [2] Number of employees refers to all employees. R - Revised.

TABLE 20 Compensation of Employees in the Paper and Allied Products Industry, from the National Income and Product Accounts

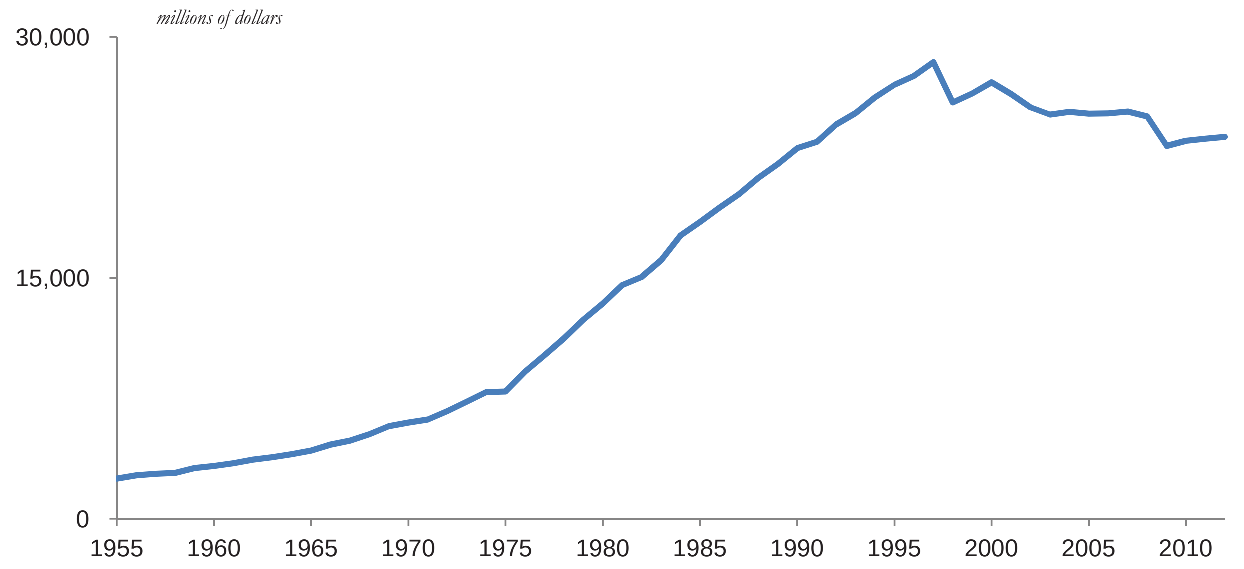
Year	Total	Wages & Salaries	Supplements to Wages & Salaries [1]	Number of Full Time Equivalent Employees	Number of Full Time & Part Time Employees	Wage & Salary Accruals per Full Time Equivalent Employee
	millions of dollars			*thousands*		*dollars*
1955	2,684	2,499	185	537	551	4,654
1960	3,596	3,288	308	576	592	5,708
1965	4,696	4,250	446	628	640	6,768
1970	6,788	5,994	794	694	702	8,637
1975	9,346	7,921	1,425	628	642	12,613
1980	16,164	13,401	2,763	681	691	19,678
1985	22,112	18,479	3,633	666	678	27,746
1990	27,848	23,063	4,785	687	697	33,514
1995	32,415	27,029	5,386	685	693	39,561
1997	33,383	28,437	4,946	675	686	42,137
1998 [2]	31,015	25,924	5,091	621	616	43,204
1999	31,697	26,486	5,211	611	607	44,878
2000	32,589	27,165	5,424	596	608	45,578
2001	32,023	26,445	5,578	564	579	46,911
2002	32,862	25,610	7,252	528	542	48,497
2003	35,854	25,172	10,682	502	516	50,192
2004	31,258	25,328	5,930	485	496	52,209
2005	31,297	25,213	6,084	469	483	53,815
2006	31,079	25,241	5,838	458	469	55,090
2007	31,378	25,345	6,033	447	457	56,640
2008	31,216	25,044	6,172	430	442	58,274
2009	28,472	23,218	5,254	393	406	59,012
2010	28,801	23,538	5,263	382	394	61,583
2011	29,343	23,667	5,676	378	388	62,679
2012	29,485	23,772	5,713	369	380	64,348

Source: U.S. Bureau of Economic Analysis, National Income and Product Accounts. Data for 2013 not available at time of publication.

[1] *Total less Wages & Salaries.*

[2] *Beginning in 1998, data based on NAICS.*

Wages and Salaries



Number of Full Time Equivalent Employees

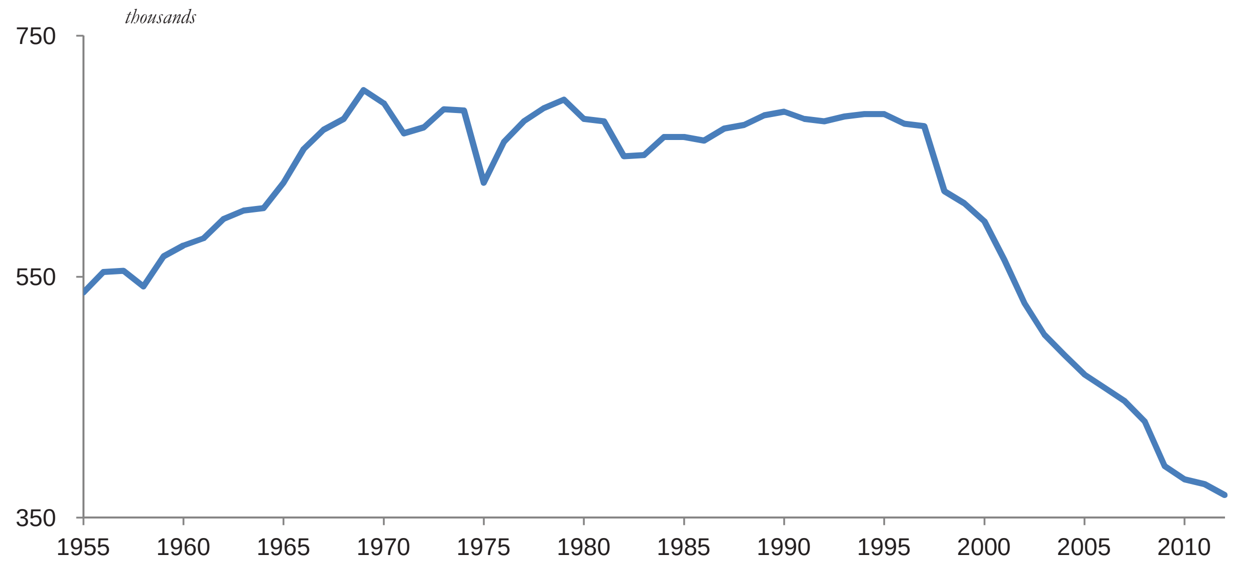


TABLE 21 A Wage Rates and Employment in the Paper and Allied Products Industry

Year	Average Hourly Earnings [1]	Average Weekly Earnings [1]	Average Weekly Hours [1]	Employees Total	Production Workers
	----------------dollars----------------			---------------thousands---------------	
PAPER AND PAPER PRODUCTS - NAICS 322					
2000	15.91	681.34	42.8	604.7	467.5
2001	16.38	690.06	42.1	577.6	446.3
2002	16.85	705.62	41.9	546.6	421.4
2003	17.33	719.55	41.5	516.2	392.7
2004	17.91	754.17	42.1	495.5	373.7
2005	17.99	764.15	42.5	484.2	365.2
2006	18.01	772.57	42.9	470.5	357.4
2007	18.44	795.58	43.1	458.2	350.5
2008	18.89	809.57	42.9	444.9	343.7
2009	19.29	806.19	41.8	407.0	313.0
2010	20.04	858.65	42.9	394.7	302.2
2011	20.28	870.53	42.9	387.4	295.3
2012 R	20.42	877.14	42.9	379.8	287.6
2013	20.31	874.44	43.1	378.7	279.9
PULP, PAPER AND PAPERBOARD MILLS - NAICS 3221					
2000	20.62	924.22	44.8	191.4	148.0
2001	21.16	930.62	44.0	179.2	139.1
2002	21.95	945.83	43.1	164.7	128.4
2003	22.62	971.07	42.9	151.0	118.1
2004	23.00	999.87	43.5	146.0	114.0
2005	22.99	1,008.33	43.9	141.6	110.7
2006	22.75	1,025.22	45.1	136.4	107.0
2007	24.03	1,071.52	44.6	132.1	104.0
2008	24.50	1,090.97	44.5	126.4	97.7
2009	24.64	1,077.13	43.7	116.9	90.8
2010	25.12	1,115.38	44.4	112.3	88.7
2011	25.75	1,174.80	45.6	109.3	85.8
2012 R	25.81	1,159.75	44.9	107.9	84.4
2013	25.00	1,122.12	44.9	107.1	81.7
PAPER AND PULP - NAICS 32212					
2000	20.68	938.58	45.4	145.6	112.8
2001	21.24	939.84	44.2	136.7	105.9
2002	21.97	954.33	43.4	124.2	96.8
2003	22.78	963.37	42.3	111.3	87.0
2004	22.96	992.63	43.2	106.8	83.4
2005	22.91	1,002.07	43.7	104.1	81.9
2006	22.95	1,032.28	45.0	99.9	78.5
2007	24.16	1,074.76	44.5	97.0	75.6
2008	24.81	1,101.73	44.4	92.1	70.2
2009 [2]	-	-	-	85.4	-
2010	-	-	-	82.5	-
2011	-	-	-	80.2	-
2012 R	-	-	-	78.8	-
2013	-	-	-	78.1	-

Source: U.S. Bureau of Labor Statistics, Employment and Earnings; data are not seasonally adjusted.

[1] *Data on hours and earnings refer to production workers.*

[2] *Data for Paper and Pulp since 2009 unavailable except for Employees Total.*

R - Revised

TABLE 21 B Wage Rates and Employment in the Paper and Allied Products Industry

Year	Average Hourly Earnings [1]	Average Weekly Earnings [1]	Average Weekly Hours [1]	Employees Total	Production Workers
	----------------dollars----------------			---------------thousands---------------	
PAPERBOARD - NAICS 32213					
2000	20.40	878.39	43.1	45.8	35.2
2001	20.90	901.41	43.1	42.5	33.2
2002	21.91	920.92	42.0	40.4	31.6
2003	22.20	992.91	44.7	39.7	31.1
2004	23.11	1020.02	44.1	39.2	30.6
2005	23.23	1025.71	44.2	37.5	28.9
2006	22.20	1005.97	45.3	36.5	28.5
2007	23.70	1061.53	44.8	35.1	28.3
2008 [2]	-	-	-	34.3	-
2009	-	-	-	31.5	-
2010	-	-	-	29.8	-
2011	-	-	-	29.1	-
2012 R	-	-	-	29.2	-
2013	-	-	-	29.0	-
CONVERTED PAPER PRODUCTS - NAICS 3222					
2000	13.58	569.03	41.9	413.2	319.5
2001	14.07	580.83	41.3	398.4	307.2
2002	14.52	600.03	41.3	382.0	293.0
2003	14.94	611.51	40.9	365.2	274.6
2004	15.57	646.31	41.5	349.6	259.8
2005	15.71	657.43	41.8	342.6	254.4
2006	15.83	664.44	42.0	334.1	250.4
2007	15.97	679.13	42.5	326.1	246.5
2008	16.54	697.65	42.2	318.5	246.0
2009	16.96	695.60	41.0	290.1	222.2
2010	17.81	751.78	42.2	282.4	213.5
2011	17.84	745.96	41.8	278.1	209.5
2012 R	18.04	759.90	42.1	271.9	203.1
2013	18.26	772.67	42.3	271.6	198.2
PAPERBOARD CONTAINERS - NAICS 32221					
2000	13.65	576.40	42.2	218.6	169.6
2001	14.11	582.82	41.3	211.3	162.5
2002	14.44	600.50	41.6	203.8	156.8
2003	14.89	617.21	41.5	195.4	147.4
2004	15.53	650.22	41.9	186.0	140.7
2005	15.49	658.33	42.5	182.3	138.5
2006	15.17	653.54	43.1	177.6	133.6
2007	15.24	658.46	43.2	172.2	130.8
2008	15.94	679.72	42.6	166.7	129.4
2009	16.43	668.63	40.7	150.7	114.6
2010	16.92	711.00	42.0	147.2	111.8
2011	16.80	705.29	42.0	145.2	110.1
2012 R	17.18	739.19	43.0	142.4	106.7
2013	17.71	776.60	43.9	143.6	104.6

Source: U.S. Bureau of Labor Statistics, Employment and Earnings; data are not seasonally adjusted.

[1] Data on hours and earnings refer to production workers.

[2] Data for Paperboard since 2008 unavailable except for Employees Total.

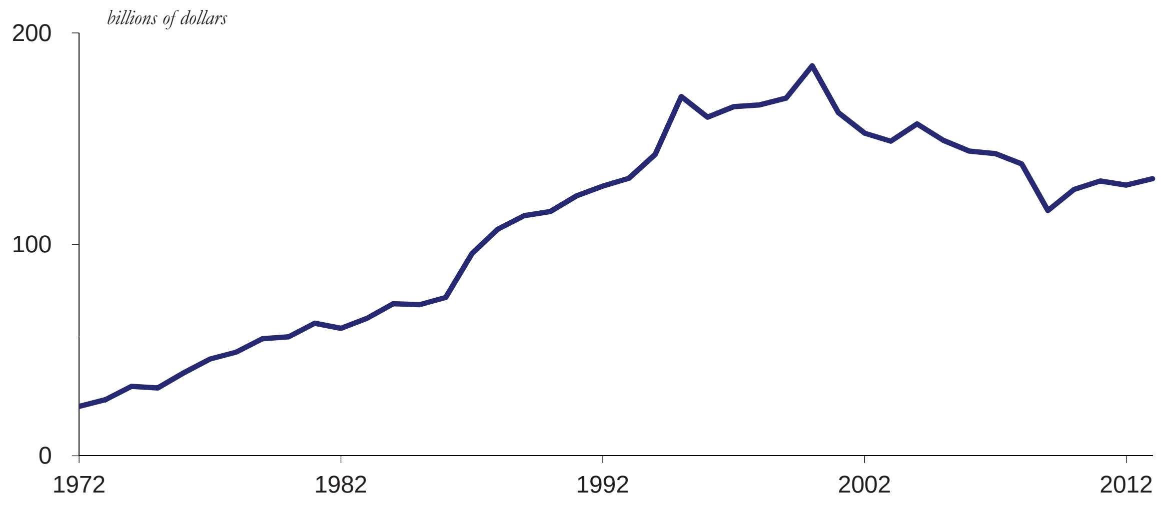
R - Revised

TABLE 22 Profit and Loss Data, Cash Inflow and Selected Balance Sheet Data for the Paper and Allied Products Industry

Year	Net Sales	Net Profit Before Taxes	Net Profit Before Taxes to Net Sales	Income Taxes	Net Profit After Taxes	Net Profit After Taxes to Net Sales	Depreciation	Cash Inflow	Gross Cash Flow
1970	21,069	1,211	5.7%	492	719	3.4%	869	1,588	2,080
1975	32,044	2,901	9.1%	1,099	1,801	5.6%	1,219	3,019	4,120
1980 E	56,250	4,045	7.2%	1,245	2,800	5.0%	2,026	4,826	6,071
1985	71,465	4,399	6.2%	1,519	2,880	4.0%	3,099	5,979	7,498
1990	115,523	7,236	6.3%	2,353	4,882	4.2%	5,578	10,460	12,814
1995	169,898	17,659	10.4%	5,680	11,979	7.1%	8,178	20,157	25,837
1997	165,149	4,926	3.0%	1,318	3,608	2.2%	9,150	12,758	14,076
1998	165,980	7,117	4.3%	2,389	4,728	2.8%	9,568	14,296	16,685
1999	169,151	10,587	6.3%	3,516	7,071	4.2%	9,438	16,509	20,025
2000	184,490	10,581	5.7%	3,149	7,431	4.0%	9,692	17,123	20,273
2001 [1]	162,234	2,388	1.5%	1,636	752	0.5%	8,825	9,577	11,213
2002	152,601	2,166	1.4%	(177)	2,343	1.5%	8,796	11,139	10,962
2003	148,804	2,249	1.5%	(160)	2,411	1.6%	8,483	10,894	10,732
2004	156,948	6,548	4.2%	1,645	4,904	3.1%	8,292	13,196	14,840
2005	149,218	6,054	4.1%	1,720	4,334	2.9%	7,360	11,694	13,414
2006	144,150	9,812	6.8%	3,681	6,134	4.3%	6,632	12,766	16,444
2007	142,889	6,304	4.4%	938	5,366	3.8%	6,710	12,076	13,014
2008	138,064	(2,136)	N.M	569	(2,706)	N.M.	6,372	3,666	4,236
2009	116,174	5,623	4.8%	1,660	3,964	3.4%	6,029	9,993	11,652
2010	125,786	8,183	6.5%	1,056	7,126	5.7%	5,781	12,907	13,964
2011	129,693	7,727	6.0%	1,597	6,130	4.7%	5,663	11,793	13,390
2012 R	127,898	7,199	5.6%	1,847	5,354	4.2%	5,599	10,953	12,798
2013	131,490	9,365	7.1%	1,030	8,335	6.3%	5,269	13,604	14,634

Notes: Cash Inflow = Net Profits After Taxes + Depreciation; Total Capital = Net Worth + Long Term Debt;
Gross Cash Flow = Net Profit Before Taxes + Depreciation; Net Cash Flow = Change in Retained Earnings + Depreciation;
E - Estimated by API with assistance from FTC; N.M. - Not Meaningful; R - Revised;
[1] U.S. Bureau of the Census converted data from the SIC system to the NAICS classification system in 2001.

Paper and Allied Products Industry Sales



millions of dollars

Cash Dividends	Change in Retained Earnings	Net Cash Flow	Total Assets	Property, Plant & Equipment Gross	Property, Plant & Equipment Net	Net Worth	Long-Term Debt	Total Capital	Net Profit After Taxes to Net Worth
430	289	1,158	19,679	18,160	9,969	10,305	4,822	15,127	7.0%
632	1,158	2,377	28,220	24,265	13,773	14,878	7,193	22,071	12.1%
1,057	1,743	3,769	45,894	40,361	24,800	24,396	10,585	34,981	11.5%
1,240	1,640	4,739	62,505	60,341	38,835	29,694	15,262	44,956	9.7%
2,351	2,530	8,108	117,335	105,489	68,726	45,951	40,720	86,671	10.6%
3,075	8,903	17,081	161,001	154,151	89,561	58,423	53,789	112,212	20.5%
3,728	(119)	9,031	178,303	158,737	96,367	60,970	61,899	122,869	5.9%
4,685	61	9,629	186,949	161,090	98,360	64,961	63,268	128,229	7.3%
3,414	3,657	13,095	203,261	161,857	97,939	68,777	68,553	137,330	10.3%
3,234	4,198	13,890	211,342	157,870	98,187	68,203	73,616	141,819	10.9%
2,465	(1,583)	7,242	194,229	161,685	89,328	65,051	67,757	132,808	1.2%
2,641	(3,722)	5,074	188,273	160,230	87,689	57,308	71,178	128,486	4.1%
3,050	(638)	7,845	188,103	157,170	82,127	60,096	71,202	131,298	4.0%
3,137	(1,115)	7,177	175,460	145,927	74,824	59,167	63,120	122,287	8.3%
3,211	(1,019)	6,341	152,472	136,148	67,628	54,266	52,221	106,487	8.0%
3,754	(3,020)	3,612	147,494	135,084	63,155	55,368	44,240	99,608	11.1%
5,246	1,355	8,065	153,493	132,845	60,452	54,821	44,617	99,438	9.8%
3,186	(14,371)	(7,999)	132,384	119,844	55,699	32,743	45,894	78,637	N.M.
2,285	739	6,768	132,937	115,854	50,199	37,622	42,474	80,096	10.5%
2,999	10,986	16,767	138,877	112,467	50,727	48,011	42,444	90,455	14.8%
3,508	(1,665)	3,998	139,030	115,056	50,744	47,095	46,402	93,497	13.0%
2,732	2,766	8,365	139,816	116,393	51,114	46,982	44,602	91,584	11.4%
3,012	4,990	10,259	143,334	115,167	49,543	52,294	44,550	96,844	15.9%

Source: Yearly data calculated by AF&PA from Quarterly Financial Report for Manufacturing, Mining and Trade Corporations, now reported by the U.S. Bureau of the Census.
2013 data is based on the First Quarter 2014 QFR Publication.

Paper and Allied Products Industry Net Profits after Taxes

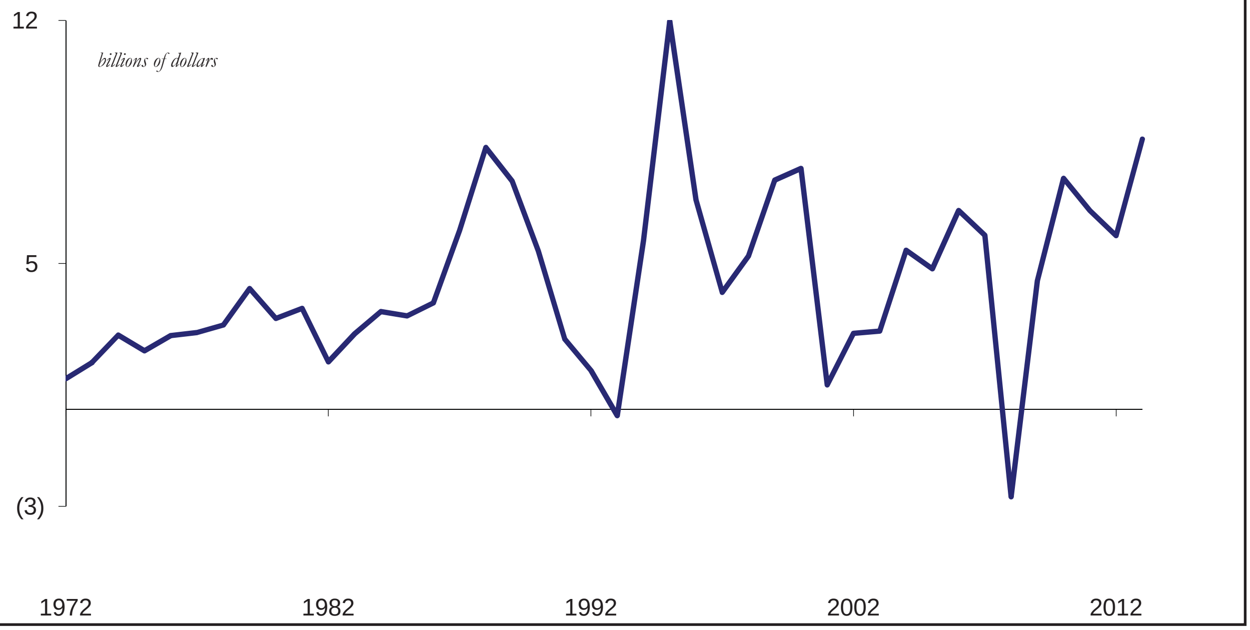


TABLE 23 General Statistics for the Paper Manufacturing Industry

General Financial Statistics 2010

	All Employees		Production Workers			Value Added by	Cost of	Value of	Capital
	Number	Payroll	Number	Hours	Wages	Manufacture	Materials	Shipments	Expenditures
	(000)	*$ millions*	*(000)*		*$ millions*				
PAPER MANUFACTURING	351.4	19,215.3	274.4	563	13,136	79,017	91,377	170,043	5,755
Pulp, Paper & Paperboard Mills	109.6	7,526	87.4	184	5,636	40,758	38,650	79,342	3,483
Pulp Mills	6.8	517	5.3	11	375	2,127	2,408	4,504	394
Paper Mills	67.7	4,501	54.7	114	3,444	25,182	22,379	47,543	1,857
Newsprint Mills						Included in Paper Mills			
Paperboard Mills	35.1	2,508	27.5	59	1,816	13,448	13,862	27,296	1,232
Converted Paper Product Manufacturing	241.9	11,689	186.9	379	7,500	38,259	52,728	90,701	2,271
Paperboard Container Manufacturing	137.5	6,777	106.6	219	4,311	19,817	30,222	49,918	1,227
Paper Bag and Coated and Treated Paper Manufacturing	51.2	2,531	38.6	77	1,555	8,750	11,188	19,773	363
Coated & Laminated Paper and Packaging Mfg	32.9	1,734	24.1	49	1,034	6,702	7,960	14,527	271
Coated, Uncoated, & Multiwall Bag and Pkg Mfg	18.3	797	14.6	28	521	2,049	3,228	5,246	92
Stationery Product Manufacturing	20.7	869	16.2	32	595	2,198	4,030	6,272	77
Other Converted Paper Product Mfg	32.5	1,512	25.6	50	1,039	7,493	7,287	14,738	605
Sanitary Paper Product Mfg	17.0	879	13.6	28	640	5,417	5,168	10,560	492
All Other Converted Paper Product Mfg	15.5	633	12.0	23	399	2,077	2,119	4,178	113

General Financial Statistics 2011

	All Employees		Production Workers			Value Added by	Cost of	Value of	Capital
	Number	Payroll	Number	Hours	Wages	Manufacture	Materials	Shipments	Expenditures
PAPER MANUFACTURING	346.5	19,268	269.2	554	13,086	81,881	94,090	175,552	6,587
Pulp, Paper & Paperboard Mills	108.0	7,575	85.5	181	5,617	42,016	40,384	82,335	3,693
Pulp Mills	6.9	520	5.4	12	359	2,481	2,799	5,263	330
Paper Mills	65.9	4,469	52.6	110	3,385	25,545	23,132	48,614	1,679
Newsprint Mills						Included in Paper Mills			
Paperboard Mills	35.2	2,586	27.6	59	1,873	13,990	14,453	28,457	1,684
Converted Paper Product Manufacturing	238.6	11,693	183.8	373	7,469	39,865	53,706	93,217	2,894
Paperboard Container Manufacturing	135.8	6,831	105.4	218	4,341	21,200	30,906	51,927	1,315
Paper Bag and Coated and Treated Paper Manufacturing	48.8	2,440	36.3	72	1,494	8,549	11,225	19,617	452
Coated & Laminated Paper and Packaging Mfg	31.4	1,695	22.9	46	1,005	6,516	8,022	14,407	340
Coated, Uncoated, & Multiwall Bag and Pkg Mfg	17.3	745	13.5	26	489	2,032	3,202	5,209	112
Stationery Product Manufacturing	20.7	847	15.9	32	570	2,443	4,064	6,487	115
Other Converted Paper Product Mfg	33.3	1,576	26.1	51	1,064	7,673	7,512	15,186	1,013
Sanitary Paper Product Mfg	17.0	905	13.4	27	654	5,693	5,396	11,092	420
All Other Converted Paper Product Mfg	16.3	671	12.6	25	410	1,980	2,116	4,094	592

Source: U.S. Bureau of the Census: Annual Survey of Manufactures, Statistics for Industry Groups and Industries.
Data for 2012-13 not available at time of publication.

TABLE 24 Value of Paper Products Manufacturers' Shipments and Inventories *millions of dollars*

Year	Paper Products	Pulp, Paper and Paperboard Mills	Paperboard Container Manufacturing	Other Paper Manufacturing
Shipments				
2001	155,845	71,987	45,817	38,041
2002	153,755	69,967	43,531	40,257
2003	151,098	68,316	43,436	39,346
2004	155,380	71,625	44,507	39,248
2005	161,928	74,888	46,184	40,856
2006	169,033	78,926	48,441	41,666
2007	176,688	80,550	50,935	45,203
2008	179,249	83,357	51,764	44,128
2009	161,636	74,397	47,326	39,913
2010	170,043	79,342	49,918	40,783
2011	175,878	82,275	51,950	41,653
2012	174,410	81,375	51,464	41,571
2013	171,356	80,086	52,271	38,999
Inventories				
2001	14,027	5,934	3,998	4,095
2002	14,286	6,496	3,912	3,878
2003	13,444	6,177	3,658	3,609
2004	14,145	6,333	4,024	3,788
2005	14,351	6,583	3,878	3,890
2006	14,937	6,649	4,055	4,233
2007	15,134	6,628	4,146	4,360
2008	15,417	6,824	4,259	4,334
2009 R	13,329	6,046	3,596	3,687
2010 R	13,873	6,262	3,739	3,872
2011 R	14,539	6,476	3,973	4,090

Source: U.S. Bureau of the Census; data are not seasonally adjusted.
Data for 2012-13 not available at time of publication. R - Revised.

Paper Products Total Shipments and Inventories

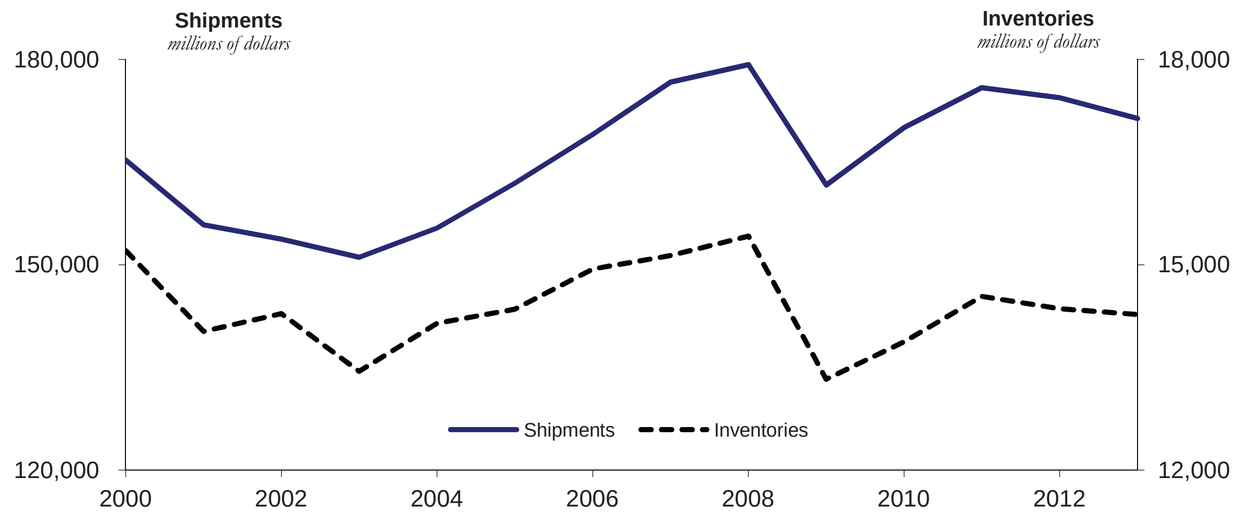


TABLE 25 General Statistics for the Paper Manufacturing Industry By State 2011

	Number of All Employees	Total Payroll	Number of Production Workers	Wages of Production Workers	Value Added by Manufacture	Value of Shipments	Capital Expenditures
	(000)	*$ millions*	*(000)*	*$ millions*			
Northeast	**61.7**	**3,387**	**47.3**	**2,250**	**12,748**	**28,313**	**913**
New England	**17.7**	**1,054**	**13.6**	**717**	**3,297**	**8,485**	**443**
Maine	6.8	432	5.5	325	1,472	4,028	328
Massachusetts	7.6	427	5.7	269	1,088	2,896	72
Connecticut	3.3	195	2.4	122	737	1,560	42
Middle Atlantic	**44.0**	**2,334**	**33.8**	**1,533**	**9,451**	**19,828**	**470**
New York	14.0	738	10.8	484	2,297	5,659	150
New Jersey	8.7	438	6.5	267	1,089	2,588	47
Pennsylvania	21.4	1,158	16.5	782	6,066	11,581	272
North Central	**110.3**	**5,812**	**85.0**	**3,853**	**23,016**	**49,554**	**1,366**
East North Central	**84.7**	**4,427**	**65.5**	**2,963**	**15,467**	**36,052**	**971**
Ohio	18.7	939	14.3	620	3,161	7,433	200
Indiana	9.9	469	7.8	316	1,450	3,901	96
Illinois	14.7	714	11.5	466	2,425	5,281	137
Michigan	10.8	567	8.5	386	1,853	4,971	124
Wisconsin	30.5	1,737	23.4	1,176	6,578	14,465	414
West North Central	**25.6**	**1,385**	**19.5**	**890**	**7,548**	**13,503**	**395**
Minnesota	11.3	676	8.4	409	3,287	5,853	179
Iowa	3.3	165	2.7	111	1,009	1,634	38
Missouri	8.0	389	6.2	271	2,814	4,886	149
Nebraska	1.5	74	1.2	50	264	592	12
Kansas	1.6	81	1.1	49	173	538	17
South	**127.8**	**7,355**	**100.5**	**5,183**	**35,016**	**73,654**	**3,505**
South Atlantic	**61.6**	**3,532**	**48.7**	**2,481**	**15,795**	**33,926**	**1,990**
Maryland	3.0	139	2.5	101	439	1,056	22
Virginia	6.9	395	5.3	270	1,462	3,490	284
North Carolina	15.7	808	12.4	565	2,815	6,644	242
South Carolina	11.3	683	8.9	488	3,239	7,138	667
Georgia	17.2	1,065	13.9	760	5,666	11,128	534
Florida	7.4	441	5.7	297	2,174	4,470	242
East South Central	**34.7**	**2,036**	**27.2**	**1,444**	**9,943**	**20,750**	**833**
Kentucky	9.0	462	6.9	301	2,130	5,014	106
Tennessee	10.8	558	8.5	397	2,478	5,205	280
Alabama	11.3	792	9.1	604	4,168	8,219	372
Mississippi	3.6	223	2.7	142	1,167	2,313	75
West South Central	**31.6**	**1,788**	**24.6**	**1,258**	**9,278**	**18,977**	**682**
Arkansas	7.7	433	6.2	322	2,479	4,569	167
Louisiana	6.7	446	5.3	330	2,614	5,300	233
Oklahoma	3.3	198	2.7	146	1,233	2,376	69
Texas	14.0	711	10.3	459	2,952	6,732	213
West	**42.1**	**2,491**	**33.0**	**1,663**	**10,128**	**22,127**	**653**
Mountain	**8.1**	**460**	**6.6**	**316**	**1,625**	**3,993**	**198**
Idaho	1.7	127	1.4	84	350	956	D
Colorado	1.3	67	0.9	44	D	428	4
Arizona	2.0	103	1.6	71	378	768	17
Utah	2.0	109	1.7	83	703	1,403	161
Nevada	1.1	52	0.9	35	195	439	16
Pacific	**34.0**	**2,032**	**26.4**	**1,347**	**8,503**	**18,134**	**455**
Washington	9.0	623	7.2	424	2,312	5,389	141
Oregon	4.1	278	3.3	196	1,554	3,097	78
California	20.8	1,131	16.0	727	4,637	9,649	236
TOTAL REPORTED	**341.9**	**19,045**	**265.9**	**12,949**	**80,908**	**173,648**	**6,437**
TOTAL U.S.A.	**346.5**	**19,268**	**269.2**	**13,086**	**81,881**	**175,552**	**6,587**

Source: U.S. Bureau of the Census: Annual Survey of Manufactures, Geographic Area Statistics.
D - Data withheld to avoid disclosure; data are included in the U.S. Totals.
Data for 2012-13 not available at time of publication.

TABLE 26 Expenditures on Plant and Equipment in the Paper Manufacturing Industry *millions of dollars*

		Primary Mills				Converting Plants				
Year	Total NAICS 322	Total Primary 3221	Pulp Mills 32211	Paper Mills 32212	Paperboard Mills 32213	Total Converting 3222	Paperboard Container Mfg. 32221	Paper Bag, CTD & Treated Paper Mfg. 32222	Stationary Product Mfg. 32223	Other Converted Paper Mfg. 32229
2001	6,797	4,373	193	3,150	1,030	2,424	1,328	481	127	488
2002	6,254	3,776	189	2,761	816	2,488	1,294	531	143	519
2003	5,999	3,690	182	2,743	765	2,309	1,210	410	94	595
2004	5,140	3,147	188	2,032	927	1,993	1,176	331	92	394
2005	5,521	3,331	139	2,238	955	2,190	1,040	549	122	479
2006	7,604	3,593	363	2,236	993	4,011	2,945	519	141	405
2007	6,602	3,667	276	2,261	1,130	2,935	1,444	821	145	526
2008	6,267	3,659	343	1,929	1,388	2,608	1,291	696	125	496
2009	4,380	2,405	264	1,272	869	1,975	947	442	81	505
2010	5,755	3,483	394	1,857	1,232	2,271	1,227	363	77	605
2011 R	6,587	3,693	330	1,679	1,684	2,894	1,315	452	115	1,013

Source: U.S. Bureau of the Census: Annual Survey of Manufactures, Statistics for Industry Groups and Industries.

Data for 2012-13 not available at time of publication. R - Revised

TABLE 27 Employment in the Paper Manufacturing Industry *thousands*

		Primary Mills				Converting Plants				
Year	Total NAICS 322	Total Primary 3221	Pulp Mills 32211	Paper Mills 32212	Paperboard Mills 32213	Total Converting 3222	Paperboard Container Mfg. 32221	Paper Bag, CTD & Treated Paper Mfg. 32222	Stationary Product Mfg. 32223	Other Converted Paper Mfg. 32229
2001	530.2	170.7	7.5	114.7	48.8	359.6	205.0	70.6	45.1	38.8
2002	491.8	159.0	8.0	102.8	48.2	332.8	184.5	66.3	38.9	43.1
2003	465.9	143.0	8.1	97.0	43.0	317.9	178.0	64.6	36.6	38.6
2004	439.2	136.6	7.7	89.2	39.7	302.5	169.0	61.0	35.7	36.9
2005	426.7	134.2	7.2	89.7	37.4	292.5	163.1	60.1	33.3	36.0
2006	413.4	127.9	6.7	85.1	36.1	285.4	161.1	56.5	31.5	36.3
2007	417.1	124.8	7.3	80.8	36.7	292.4	165.8	60.1	31.3	35.1
2008	403.7	118.5	7.5	76.7	34.3	285.2	164.6	57.8	28.9	33.9
2009	362.6	113.4	6.5	72.0	34.9	249.2	142.4	50.4	24.1	32.4
2010	351.4	109.6	6.8	67.7	35.1	241.9	137.5	51.2	20.7	32.5
2011 R	346.5	108.0	6.9	65.9	35.2	238.6	135.8	48.8	20.7	33.3

Source: U.S. Bureau of the Census: Annual Survey of Manufactures, Statistics for Industry Groups and Industries.

Data for 2012-13 not available at time of publication. R - Revised

[1] Number of employees refers to all employees.

SECTION IV - EMPLOYMENT, WAGE AND PRODUCTIVITY RELATED DATA

Page 29: State Employment Data for the Paper Manufacturing Industry
U.S. Bureau of the Census, Annual Survey of Manufactures
www.census.gov/manufacturing/asm/index.html
Go to "Statistics for All Manufacturing by State"

Page 30: Compensation of Employees in the Paper and Allied Products Industry, from the National Income and Product Accounts
U.S. Bureau of Economic Analysis, National Data
http://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1
From the list of all NIPA tables, Section 6--Income and Employment by Industry, see 6.2D - 6.6D.

Pages 32- 33: Wage Rates and Employment in the Paper and Allied Products Industry
U.S. Bureau of Labor Statistics
www.bls.gov/data/home.htm
Go to "Employment, Hours, and Earnings - National" and click on "One-Screen Data Search" to build a query.

SECTION V - FINANCIAL AND CAPITAL EXPENDITURE RELATED DATA

Pages 34 -35: Profit and Loss Data, Cash Inflow and Selected Balance Sheet Data for the Paper and Allied Products Industry
U.S. Bureau of the Census, Quarterly Financial Report
www.census.gov/econ/qfr/historicpub.html
Note: Annual figures in Table 22 are based on data for each quarter in the QFR.

Page 36: General Statistics for the Paper Manufacturing Industry
U.S. Bureau of the Census, Annual Survey of Manufactures
www.census.gov/manufacturing/asm/index.html
Go to "Statistics for Industry Groups and Industries"

Page 37: Value of Paper Products Manufacturers' Shipments and Inventories
U.S. Bureau of the Census, Manufacturers Shipments, Inventories, and New Orders
www.census.gov/manufacturing/m3/historical_data/index.html
Download the "Shipments" and "Total Inventory" Excel files.
Refer to the 6-digit M3 Series Identification Codes on the website to navigate through the files.

Page 38: General Statistics for the Paper Manufacturing Industry by State
U.S. Bureau of the Census, Annual Survey of Manufactures
www.census.gov/manufacturing/asm/index.html
Go to "Statistics for All Manufacturing by State"

Page 39: Capital Expenditures and Employment in the Paper Manufacturing Industry by Sector *(based on NAICS)*
U.S. Bureau of the Census, Annual Survey of Manufactures
www.census.gov/manufacturing/asm/index.html
Go to "Statistics for Industry Groups and Industries"

OTHER GOVERNMENT SOURCES

Producer Price Index for Commodity Groupings and Individual Items
U.S. Bureau of Labor Statistics
www.bls.gov/ppi/home.htm
Under "PPI Databases," go to "Commodity Data" and click on "One-Screen Data Search" to build a query.

Producer Price Index for the Net Output of Selected Industries and Products
U.S. Bureau of Labor Statistics
www.bls.gov/ppi/home.htm
Under "PPI Databases," go to "Industry Data" and click on "One-Screen Data Search" to build a query.

PAPER GRADES

NEWSPRINT

Uncoated paper used for the printing of newspapers, traditionally made from a furnish containing at least 65% mechanical pulps, unsized or very lightly sized having a smoothness on each side not exceeding 200 seconds Bekk, weighing not less than 40g per square meter and not more than 65g per square meter and having an ash content by weight not exceeding eight percent. Does not include printing papers of types generally used for purposes other than newspapers such as mechanical printing papers for catalogs, directories, inserts, etc.

PRINTING & WRITING and RELATED PAPERS

Coated or uncoated paper used primarily for the purpose of printing, writing, or other type of communications. This includes Bristols manufactured for non-packaging purposes but does not include newsprint.

Uncoated Mechanical: Uncoated papers usually containing more than 10% mechanical pulps (stone groundwood, refiner or thermomechanical) in their furnish, excluding newsprint.

Coated Mechanical: Bleached papers traditionally containing more than 10% mechanical pulp in their furnish and with a coating weight of at least 2.5 pounds (25 x 38-500) on either side and at least 50% of the coating consisting of pigment. Surface coatings are added for the purpose of improving the appearance and printing surface. The coater can be on or off the machine.

Coated Free Sheet: Bleached paper traditionally containing not more than 10% mechanical pulps in their furnish and with a coating weight of at least 2.5 pounds (25 x 38-500) on either side (or on one side in the case of one-sided grades) and at least 50% of the coating consisting of pigment. Surface coatings are added for the purpose of improving the appearance and printing surface. The coater can be on or off the machine.

Uncoated Free Sheet: Bleached uncoated papers usually containing not more than 10% mechanical pulps in their furnish; includes offset, tablet, envelope, business papers (bond, ledger, mimeo, duplicator), forms bond, cover and text, and related papers. Also includes "thin papers" - carbonizing, bible, stencil, and similar papers.

Solid Bleached Bristols: Heavyweight paper, coated or uncoated, used primarily for graphic communications and for business office and school supplies. Includes tabulating index, tag, file folder, index, postcard, and coated cover bristols.

Cotton Fiber: Papers containing 25% or more in their furnish of cotton, cotton rags, cotton waste, linters, linter pulp, flax, or similar fibers.

PACKAGING & INDUSTRIAL CONVERTING

Wrapping paper, shipping sack, bag and sack other than shipping sack, and other converting papers. Also includes paper and board used in specialty packaging and industrial end uses.

Unbleached Kraft: Paper traditionally containing more than 80% unbleached sulfate wood pulp. Includes wrapping paper, shipping sack, grocers sack and other bag, and other converting papers -18 lbs. and over (24 x 36-500).

Bleached Packaging and Industrial Converting: Paper made for similar end uses as unbleached Kraft, but made from bleached, and semi-bleached sulfate and unbleached sulfite pulps. Includes wrapping paper, shipping sack, grocers and other bag and sack, and other converting papers -18 lbs. and over (24 x 36-500).

Specialty Packaging: Paper and board of all weights and furnishes, usually used as protective packaging for food and other consumer products, such as bakery bags, fast food and frozen food wraps. Also includes glassine, greaseproof and some vegetable parchment paper.

Special Industrial: Paper and board, of all weights, calipers and furnishes, designed for specialized end uses and manufactured to exact customer specifications; includes abrasive paper, electrical insulation, filter paper, and similar grades. Does not include wet machine board.

TISSUE

Includes sanitary grades, such as toilet, facial, napkin, toweling, sanitary napkins, wiper and special sanitary papers, waxing, wrapping, wadding, and miscellaneous grades.

PAPERBOARD GRADES

UNBLEACHED KRAFT PAPERBOARD

Paperboard made from a furnish containing not less than 80% wood pulp produced by the sulfate process.

Linerboard: Unbleached Kraft paperboard used as facing material in the manufacture of corrugated or solid fiber boxes. Includes solid unbleached Kraft linerboard, white top linerboard and clay coated unbleached Kraft linerboard.

Folding: Paperboard, such as clay coated unbleached Kraft and bleached lined unbleached Kraft backed, manufactured for conversion into folding cartons and beverage carriers.

Other: All unbleached Kraft paperboard whose end use is not otherwise classified, such as board to be fabricated into a shipping container, tube, can, drum, file folder, tag, automotive panel, etc.

SOLID BLEACHED PACKAGING PAPERBOARD

Paperboard for use in packaging made from a furnish containing not less than 80% bleached wood pulp. Bleached bristols manufactured for non-packaging uses are included in the bleached bristol classification under paper grades.

Linerboard: Solid bleached paperboard used as facing material in the manufacture of corrugated or solid fiber boxes.

Folding: Solid bleached paperboard for conversion into folding cartons, such as folding cartons for ice cream, butter, margarine, frozen foods, bakery products, cosmetics, drugs, etc.

Liquid Packaging and Food Service:
Liquid Packaging - Solid bleached paperboard for conversion into cartons packaging fluids which are packed fresh or aseptically, such as milk, cream and fruit juices. May be waxed, coated, laminated, extruded or otherwise treated.
Food Service - Solid bleached paperboard for conversion into cups and round nested food containers, plates, dishes and trays, and packaging for moist, liquid or oily foods.

Other: Solid bleached paperboard for conversion into products like can stock, milk bottle hood and lip cover (snap-in or coverall type), cup lid, milk bottle plug, layers separator stock, bacon boards, meat pads, blister packs, tubes, etc., other products not classified above and industrial products not classified under bleached bristols.

SEMICHEMICAL PAPERBOARD

Paperboard made from a furnish traditionally containing not less than 75% wood pulp, the predominant portion of which is produced by a semichemical process.

Corrugating Medium: Semichemical paperboard used as the fluting material in the manufacture of corrugated or solid fiber boxes.

RECYCLED PAPERBOARD

Paperboard manufactured from a combination of recycled fibers from various grades of paper stock with the predominant portion of its furnish being recycled fibers; sometimes includes wood pulp as described below.

Linerboard: Recycled paperboard produced from a furnish usually containing less than 80% wood pulp and used as facing material in the manufacture of corrugated or solid fiber boxes.

Corrugating Medium: Recycled paperboard produced from a furnish traditionally containing less than 75% wood pulp and used as the fluting material in the manufacture of corrugated or solid fiber boxes. Also includes container chip and filler board.

Folding: Recycled paperboard manufactured with bending quality for conversion into folding cartons (including unlined chipboard, Kraft lined, white lined and clay coated).

Set-Up: Recycled paperboard manufactured with non-bending specifications for conversion into rigid or set-up boxes (including plain chipboard, newslined and white vat lined).

Gypsum Wallboard Facing: Recycled paperboard manufactured for use as liner or facing on gypsum board and plasterboard (includes white, cream, gray, blue and all colors).

Other: Recycled paperboard with the same characteristics as paperboard for folding and set-up, but mostly used in non-packaging applications. Also includes recycled paperboard for uses not otherwise classified. Examples of end uses include panelboard, commercial printing pre-printed board, tag, file folder, tube, can, drum, match, stem, tablet backs, toys, etc.

CONSTRUCTION PAPER & BOARD

CONSTRUCTION PAPER

Sheathing paper, felts (roofing felts, floor covering, automotive felts, deadening, industrial, pipe covering, refrigerator, etc.), flexible wood fiber insulation.

WET MACHINE BOARD

Binders board, shoe board (e.g., counter board, heel board, innersole, etc.), automotive board, chair seat backing, coaster board, luggage, mill board, panel board, table top board, etc.

INSULATING BOARD

A fibrous-felted homogenous panel made by interfelting of the fibers (e.g., interior building board, wallboard, sound deadening board, acoustical tile, exterior sheathing board, roof insulation board, trailer board, etc.).

WOOD PULP

DISSOLVING & SPECIAL ALPHA

Highly refined bleached white sulfite or sulfate pulp with a high content of alpha (pure cellulose) fiber.

SULFITE PAPER GRADES

Paper grade pulps produced by the sulfite process. Bleached pulp must achieve a G.E. Brightness of more than 75.

SULFATE PAPER GRADES

Bleached Hardwood, Bleached Softwood, Unbleached Sulfate: Paper grade and fluff pulps produced by the sulfate or soda process. Bleached pulp must achieve a G.E. Brightness of more than 75. Semi-bleached pulp must achieve a G.E. Brightness of not less than 45 nor more than 75. Unbleached pulp has a G.E. Brightness of less than 45.

SEMICHEMICAL

High yield pulps produced with the use of some chemical agent such as neutral sulfite (N.S.S.C.), alkaline cook, chemipulp (defibrated pulp put through reaction chambers), or chemimechanical pulp, with a yield usually above 60%.

MECHANICAL

Fine textured, usually bright pulps, used in paper and paperboard manufacture and produced by mechanical rather than chemical processes.

Stone Groundwood: Pulp produced by grinding wood logs or bolts (usually 4 ft. in length) into relatively short fibers.

Refiner: Pulp produced by subjecting wood chips and/or residues to atmospheric or open discharge refining.

Thermomechanical: A high-yield pulp produced by a thermomechanical process in which wood particles are softened by preheating under pressure prior to pressurized primary refining stage. Usually replaces or reduces the chemical pulp component in newsprint or mechanical papers.

WOOD PULP FOR CONSTRUCTION PAPER & BOARD

Coarse, often brown, pulps used in the manufacture of insulating board and construction paper. Also includes similar pulps if used in the manufacture of wet machine board. Excludes pulp for hard pressed board.

Stone Groundwood and Refiner: Pulps produced by the stone groundwood or refiner processes but used in the manufacture of construction paper and board.

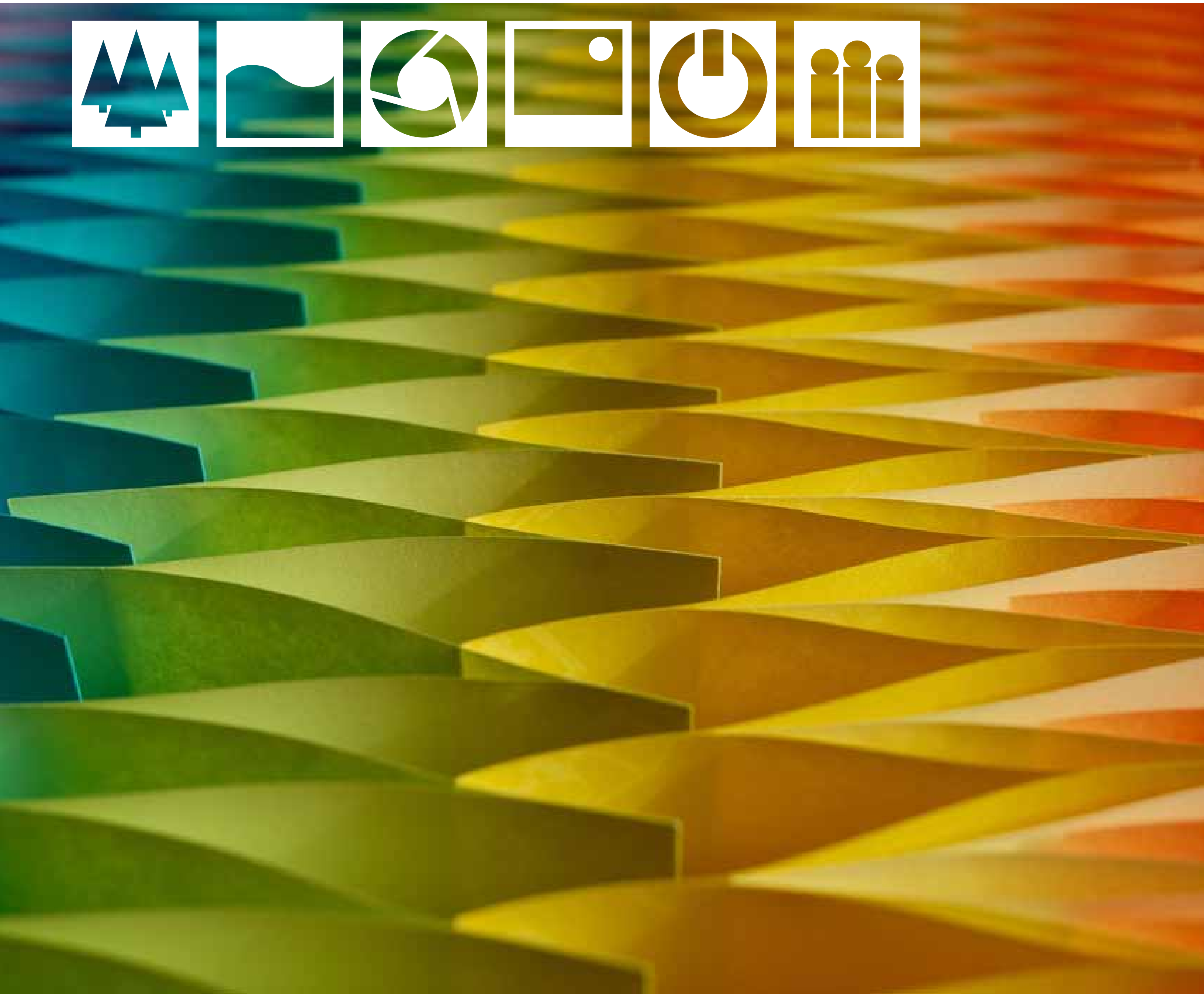
Defibrated/Exploded: Pulps produced by subjecting wood chips to preheating and pressurized refining. Similar to the thermomechanical process except that operation variables produce an economical, coarse brown pulp suitable only for construction paper and board.

Appendix C

BETTER PRACTICES
BETTER PLANET 2020
Continuing AF&PA's Commitment to Sustainability

American
Forest & Paper
Association

2014 AF&PA Sustainability Report



Introduction

The American Forest & Paper Association (AF&PA) has a long history of achievement in, and reporting transparently on, sustainability actions taken by the industry. Our members are committed to using sustainable manufacturing processes to produce reusable and recyclable products from a sustainably-managed renewable resource. People across the country and around the world rely on our products to communicate and inform, provide shelter and hygiene, package and deliver necessities, and capture life's memorable moments.

AF&PA members represent the diverse spectrum of the forest products industry — ranging from large to small, publicly and privately owned, U.S. and global companies that manufacture pulp, paper, packaging and wood products, and some that own and manage forests. These member companies are an integral part of the communities in which they operate, contributing to community leadership, education, health and wellness, and recreational opportunities. The jobs our members provide are a vital driver of the overall economic health of those communities.

AF&PA's sustainability efforts help member companies strive toward their own sustainability goals by providing:

- Environmental, Health & Safety (EHS) Principles, as well as Sustainable Forest Management and Sustainable Procurement Principles for wood sourcing. AF&PA members comply with these principles as a condition of membership;
- Periodic tracking of progress towards sustainability performance through a set of economic, social, and environmental indicators;
- Initiatives such as *Better Practices, Better Planet 2020* that establish sustainability goals for the combined AF&PA membership; and
- Forums for industry, governments, communities, and others to work together towards improved sustainability performance for the benefit of all stakeholders.

We report biennially on AF&PA members' sustainability performance. This reporting reaches beyond environmental performance to also integrate the economic and social elements essential to our industry's viability and the communities and families that we support. We have made great strides to continue our proven performance and push to reach new heights.

One of the best examples of our focus on continued improvement is AF&PA members' commitment to the goals within our sustainability initiative — *Better Practices, Better Planet 2020* — which includes one of the most extensive collections of quantifiable sustainability goals for a major U.S. manufacturing industry.

AF&PA received three **Green Globes®** for the build-out of our new office space in Washington, D.C. The rating system is an online program for green building certification that uses third-party assessors and evaluates environmental impacts. AF&PA's three Green Globes awards demonstrate leadership in applying best practices regarding energy, water, and environmental efficiency. The new offices feature extensive use of daylight; energy-efficient lighting and mechanical systems; low-emitting paints, coatings, adhesives and flooring; and the incorporation of wood and paper-based design elements.

Our members continuously strive for improved performance, which we recognize through annual AF&PA Sustainability Awards. These awards encourage and recognize exemplary industry programs and initiatives contributing to innovation in sustainable processes and procurement.

We are proud to represent member companies who take seriously their commitment to sustainability.

Donna Harman

Donna Harman
President and CEO
July 2014

BETTER PRACTICES
BETTER PLANET 2020
Continuing AF&PA's Commitment to Sustainability

Progress toward the *Better Practices, Better Planet 2020* sustainability goals:

GOAL: Exceed 70 percent rate of paper recovery for recycling by 2020
Paper recovery for recycling reached 63.5 percent in 2013 — exceeding 60 percent for the past 5 years.

GOAL: Improve members' purchased energy efficiency use by at least 10 percent from 2005 to 2020
Improved energy efficiency led to a reduction in purchased energy of 8.8 percent. On average, about two-thirds of our members' energy needed for forest products production comes from the use of carbon-neutral biomass.

GOAL: Reduce our members' greenhouse gas emissions by at least 15 percent from 2005 to 2020
Greenhouse gas emissions were reduced by 14.5 percent — nearly reaching our goal!

GOAL: Increase the amount of fiber procured from certified forestlands or through certified fiber sourcing programs in the U.S. from 2005 to 2020 and work to decrease illegal logging
AF&PA members' procurement of fiber from certified forestlands reached 29 percent, and fiber procured through certified programs reached 95 percent. Members also continue to support programs to decrease illegal logging.

GOAL: A vision for the industry of zero injuries and measuring progress toward that vision by further improving our incidence rate by 25 percent from 2006 to 2020
The safety incidence rate in our facilities improved by 24 percent.

GOAL: Reduce water use in members' pulp and paper mills by 12 percent from 2005 to 2020
Water use at member pulp and paper mills was reduced by 6 percent.

The Forest Products Industry's Sustainable Record

The American Forest & Paper Association (AF&PA) is proud to present our 2014 Sustainability Report documenting the sustainability performance of AF&PA member companies, representing the U.S. pulp, paper, packaging, and wood products manufacturing industry. This report outlines the social, economic, and environmental contributions made by our members, as well as the performance metrics that show the positive actions taken to improve the efficiencies of our processes. Information contained in this report was obtained through AF&PA's most recent surveys collecting data on environment, energy, health and safety, and certified fiber, as well as from public sources.[1]

Our industry seeks to preserve and grow its economic contribution, and that of the individual companies, to society; works to foster the well-being of our communities; and uses sustainable manufacturing and fiber procurement practices to protect the environment, ensuring that our resources will be available to meet the needs of future generations.

Unique qualities that characterize our industry include:

- The essential bio-based products produced by our members that support and protect everyday life in our society;
- Increased efficiencies in our production and use of energy, reductions of our carbon footprint, and substantial reductions in the release of environmental pollutants; and
- Planning for the future through development and production of new bio-based products.

Sustainability advocates and practitioners have worked to refine the concept for decades. In 1987, the United Nations World Commission on Environment and Development (the Brundtland Commission) defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Over time, the understanding of sustainability has matured. While in the past there has been a primary focus on the environmental elements, it is now broadly recognized that the social and economic elements must be pursued equally if we are to achieve long-term sustainability.[2]

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[1] Unless stated otherwise, data are from the survey results for the 2012 operating year.

[2] United Nations (2013) *Global Sustainable Development Report – Building the Common Future We Want*. New York: United Nations Department of Economic and Social Affairs, Division for Sustainable Development. 2013, http://sustainabledevelopment.un.org/globalsdreport/

Providing Society's Essential Products

Forest products are essential components of modern life. They are made from a renewable resource — trees. They encompass an incredibly wide range of products with nearly limitless everyday uses from facilitating education, communications, hygiene, food storage, and product protection to providing shelter and homes. New and innovative forest products are being developed while constant improvements are made to existing products.

- Printing and writing papers include paper used for books, magazines, office and home printers, birthday cards, wedding invitations, printed photos and vital documents, such as birth certificates, social security cards, and diplomas. These papers have continually adapted to fit the needs of each new generation, serving an important role in enabling the flow and exchange of information throughout all sectors of society and around the world.

Sustainability Award Winner

Graphic Packaging International developed an innovative packaging solution for 12 and 18 bottle beer packs, reducing greenhouse gas emissions by 30 percent and glass bottle breakage without increasing total packaging materials. The "Tite-Pak® Innovation Beverage Packaging" project won the 2013 Innovation in Sustainability Award from AF&PA.

- Paper-based packaging is a versatile and cost-efficient method to transport, protect and preserve a wide array of items. It is engineered to be sturdy, yet lightweight, and is customizable to meet product- or customer-specific needs. Corrugated containerboard is used to ship and transport everything from electronics to fragile glassware to perishable goods; paperboard packages food, medicine and toiletries for handy storage and display; and paper bags give customers a sustainable option to carry their purchases home.
- Wood provides shelter, furniture, flooring, and cabinetry, as well as smaller items from bowls to toys to chopsticks. It is the building material of choice for strength, aesthetic appeal and environmental responsibility. In addition, wood stores carbon and is less energy- and carbon-intensive to produce than competing materials like concrete and steel.

Economic Contributions — a Critical Element of Sustainability

In 2012, the forest products industry (paper, paperboard, converting and wood products) contributed almost 4 percent of the U.S. manufacturing gross domestic product (GDP). Sector sales totaled $210 billion in 2013, and the industry paid estimated state and local taxes of $4.6 billion.

In the U.S., the industry's employment of nearly 900,000 people exceeds employment levels of the automotive, chemical, and plastics sectors. The forest products industry pays approximately $50 billion a year in wages and other compensation.

In the small, rural communities where our mills generally are located, these are highly sought after, well-paying jobs. Indeed, more than 75 percent of U.S. pulp and paper mills are located in counties designated by the U.S. Census Bureau as more than 80 percent rural.[3] These jobs play a key role in the standard of living, education, and cultural fabric of the area.

Wages at pulp and paper mills are 50 percent higher than the average private sector job.[4] In addition, every 100 paper industry jobs supports 325 additional jobs in supplier industries and within local communities.[5]

In 2009, the U.S. paper, paperboard, and converted products sector achieved a positive trade balance for the first time in nearly 100 years. In 2013, exports exceeded imports by 2.6 million tons.

Efficiency is essential to international competitiveness. From 2001 to 2011, worker productivity rose 36 percent at pulp, paper, and paperboard mills. The productivity contributions of our workers are critical to the U.S. industry's ability to compete in the world marketplace.

Forest Products Industry Labor Productivity Gains

SOURCE: U.S. Bureau of Labor Statistics

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[3] The U.S. Census Bureau basically defines rural in two forms, as: 1) census designated areas having "less than 2,500 persons"; and 2) "other places" based on housing units and other demographic information.

[4] Calculated by AF&PA using December 2013 Bureau of Labor Statistics payroll data.

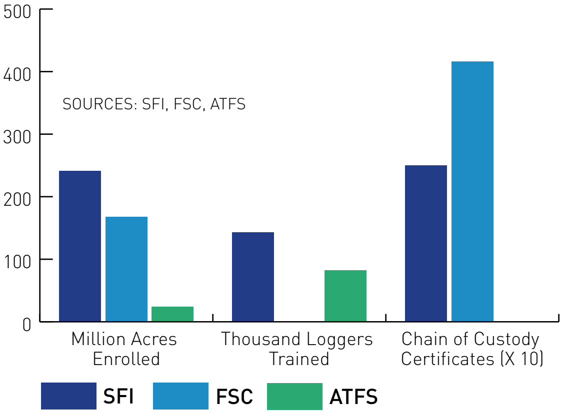
[5] *Updated Job Multipliers for the U.S. Economy* (table 9), Economic Policy Institute, August 2003.

AF&PA members operate in a very competitive global market. To enhance our sustainability, we are working to take advantage of our strengths and to find additional opportunities for our unique bio-based supply chain to produce new products and other applications for our existing products.

Sustainable Use of Wood — Our Basic Raw Material

Trees are the ultimate renewable resource because they can be planted, grown, harvested and replanted. AF&PA members have long supported and followed sustainable forestry practices. More than 20 years ago, members agreed to adhere to a set of Sustainable Procurement Principles that reach far beyond legal requirements. The Principles encourage members to procure wood fiber from suppliers trained in sustainable forestry practices and principles and who use qualified logging professionals; provide research funding for forestry; and seek to improve forest management practices. Additional work led to the development of a sustainable forestry standard, which later became the Sustainable Forestry Initiative (SFI®), an independent non-profit. Today, AF&PA members use standards and methods developed and maintained by the SFI®, the Forest Stewardship Council (FSC®), the American Tree Farm System (ATFS), and the Programme for the Endorsement of Forest Certification (PEFC™). For us, sustainability is not just an option; it's a necessity for maintaining forest resources into the future.

2013 North American Sustainable Forestry Management Program Statistics



Sustainability Award Winner

Domtar formed the Four States Timberland Owners Association in 2010 to educate landowners and managers on how to obtain sustainable forest management certification. Domtar, along with 55 individual landowners owning more than 70,000 acres, achieved certification of their forestland. AF&PA awarded Domtar the 2013 Leadership in Sustainability Sustainable Forestry Management Award for this project.

The photosynthesis associated with tree growth captures and converts carbon dioxide from the atmosphere into fiber and other wood components. Wood stores carbon indefinitely, even as a finished product, helping to reduce the effects of greenhouse gas emissions over the long haul. In addition, growing trees also release oxygen into the atmosphere, thereby supporting life on our planet. In 2011, U.S. forests and wood products captured and stored roughly 16 percent of all carbon dioxide emitted by fossil fuel consumption in the United States.[6]

More trees are planted annually in the U.S. than are harvested by the forest products industry. Currently, 1.2 billion trees are planted per year according to the U.S. Forest Service.[7] Today, the United States has 20 percent more trees than it did on the first Earth Day celebration more than 40 years ago. One-third of the United States is forested — 751 million acres.

Privately-owned forests supply 91 percent of the wood used by the U.S. forest products industry, while state, tribal and municipal forests supply 7 percent, and federal forests supply only 2 percent. More than 56 percent of U.S. forests are privately owned, much of it by family forest owners who manage their lands to provide value for future generations. Maintaining a healthy and economically viable forest products industry business sector creates a market for wood, providing an incentive for landowners to keep land forested rather than convert it to other uses such as development or agriculture. It also provides a profitable market outlet for removing trees to reduce overcrowding, which helps to maintain healthy, resilient forests, which in turn reduces wildfires and insect and disease infestations.

The reforestation activities that take place on managed lands after harvest provide numerous ecological and social benefits not possible if forest stands are left in the mature state. Each stage of the forest succession process provides unique habitat and environmental protection benefits that would not occur without the rotational harvest and reforestation cycles.

Sustainability Award Winner

Green Bay Packaging achieved 100 percent fiber yield recovery at its Arkansas Kraft Division facility and was recognized by AF&PA with the 2012 Innovation in Sustainability Award. The mill attained zero-landfill of fiber collected in the mill waste treatment system, diverting over 60,000 cubic yards of usable fiber from landfills in 2011.

Sustainable Manufacturing

Our commitment to sustainable manufacturing is one of the most significant of any industrial sector, and AF&PA's *Better Practices, Better Planet 2020* sustainability initiative includes one of the most extensive collections of quantifiable goals for a major U.S. manufacturing industry. Our members created this program to focus on achieving a suite of six sustainability goals (see Part II for a goals progress report).

But progress on our goals only tells part of the story. Sustainable manufacturing is an economic as well as environmental imperative for AF&PA members. Efforts to improve the efficiency of how we use

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[6] *Climate Changes in the United States, Third National Climate Assessment*, May 2014.

[7] *Forest nursery seedling production in the United States—fiscal year 2012* – USDA Forest Service, 2013.

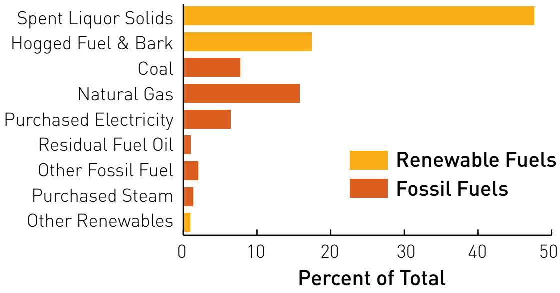
resources have resulted in decreased emissions and natural resources needed to manufacture our products. For example, wood fibers used to make a sheet of paper are separated and prepared in water-based slurries. Water and other materials are added and then removed to produce the finished paper, thus recycling and reusing raw materials. Water is reused 10 times before being treated and returned to the environment. Spent pulping chemicals and organic substances from the biomass material are combusted to capture and reuse the pulping chemicals and to generate valuable carbon neutral fuel to power our mills. At kraft pulp mills (the most commonly used process in the U.S.), up to 98 percent of the pulping chemicals are recovered and recycled in virtually a closed loop.

Renewable Energy and Energy Efficiency

AF&PA members strive to minimize energy costs, as energy constitutes the third largest expense category for the forest products industry (with the cost of materials such as fiber ranking number one and employee compensation number two).

Member mills produce solid wood products, pulp, paper, paper-based packaging, and other wood-based materials. Residuals that do not end up in products can be used as an energy source for manufacturing or used to generate electricity that is sold to the grid as green power.

We self-generate most of our energy needs; more importantly, most of that is renewable energy. On average, about 66 percent of the energy used at AF&PA member pulp and paper mills is generated from carbon-neutral biomass. In fact, forest and paper products facilities accounted for 62 percent of the renewable biomass energy consumed by all manufacturing facilities in all sectors. Fifty-nine percent of the electricity used by our members was self-generated. Indeed, 42 percent of our members' mills self-generated more than half of their power, and 23 percent sold excess power back to the grid, much of it renewable as well.

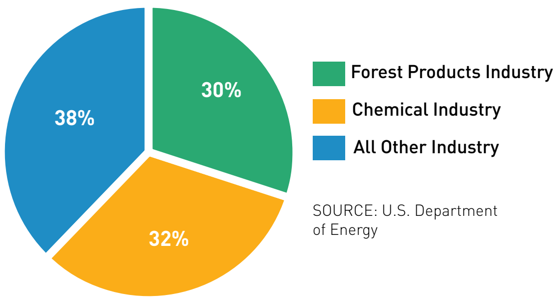


2012 Pulp and Paper Mill Energy Sources

The industry has long relied on the much more efficient combined heat and power (CHP) generation process to produce the electricity and steam needed to manufacture its products. In this process, exhaust steam from electricity-generating turbines is used directly to dry wood and paper and to heat production processes or buildings before being condensed and recycled back to steam generation boilers. The use of CHP results in efficiencies in the range of 50 to 80 percent at forest products plants, in comparison to non-CHP electrical stations, such as utilities, with typical efficiencies around 33 percent. In 2012, 96.4 percent of the electricity the industry generated was through CHP. The forest products industry produced 30 percent of CHP electricity generated by manufacturing facilities in the U.S. Of all manufacturing sectors, only the chemical industry produced more.

Sustainability Award Winner

A comprehensive, multi-year energy management program developed for **Georgia-Pacific**'s manufacturing facilities spawned more than 200 energy efficiency projects and other efforts. Collectively, they generated savings of more than $50 million in purchased energy and reduced energy use by over two trillion Btu. These results and the resultant greenhouse gas reductions were recognized by AF&PA with a 2012 Leadership in Sustainability Energy Efficiency/Greenhouse Gas Reduction Award.



2012 CHP Electricity Generation by Industry

SOURCE: U.S. Department of Energy

Water

Water is a vital part of the papermaking process. Technology and innovation enable water to be reused and recycled ten times throughout the paper mill process.

After water is used inside the mill, it is treated in a wastewater system and then returned to the environment. The forest products industry directly returns to the environment about 88 percent of the water it withdraws and uses in its manufacturing processes. Another 11 percent evaporates, once again becoming part of the water cycle. The remaining one percent is incorporated into our products.

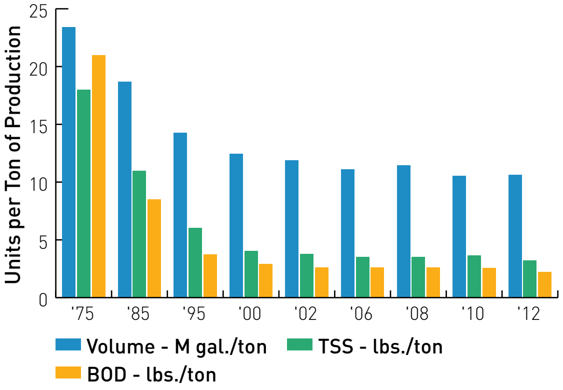
AF&PA shares the global concerns about water scarcity and access to potable water. The environmental impacts of water use and the economic and social aspects of that use are very site-specific. We have actively participated in global water sustainability initiatives to help advance understanding of the impacts of water use at our mills, as we believe that it is the impact of that use — which includes positive economic impacts — that is most important. We have participated in the development of the Alliance for Water Stewardship's International Water Stewardship Standard released in April 2014, as well as the Water Footprint Standard developed by the Water Footprint Network and its partners.

While we focus on achieving our water use reduction goal, we continue to make progress reducing the regulated constituents in our water discharges. For example, compared to 2010, total suspended solids (TSS) releases were reduced by 11.5 percent and Biochemical Oxygen Demand (BOD), a measure of the amount of organic material in the effluent that results in lowered oxygen content of receiving streams, was reduced by 12.9 percent.

Sustainability Award Winner

The 2012 AF&PA Leadership in Sustainability Water Award winner, **MWV's Mahrt Mill** in Cottonton, Alabama, reduced water usage by 20 percent, energy usage by over 8 percent, and CO$_2$ emissions by 10 metric tons per day while maintaining existing production quality and capacity.

Pulp and Paper Mill Effluent Discharges

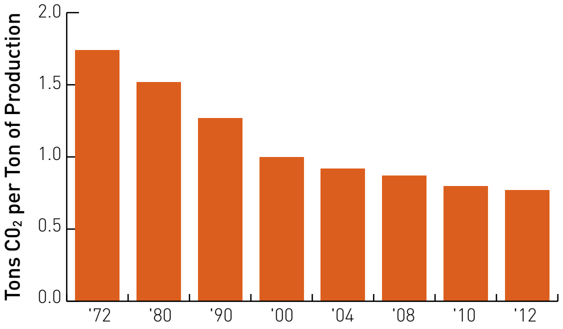


Greenhouse Gas (GHG) Emissions

The carbon-neutral renewable energy generated by our members is equivalent to 200 million barrels of oil annually, and its use avoids fossil fuel-based GHG emissions. Virtually all of this energy comes from biomass residuals left over from the manufacturing process; diverting these residuals from landfills also curbs potential GHG emissions.

At pulp and paper mills, the emission rate expressed in tons of carbon dioxide (CO$_2$) equivalents per ton of production has been reduced by 55.8 percent since 1972, 23.1 percent since 2000, and 3.9 percent compared to 2010. The emissions intensity rate for pulp and paper mills and wood products facilities combined decreased by 22.5 percent since 2000. Between 2010 and 2012, this rate was reduced by 4.4 percent.

Pulp and Paper Mill Greenhouse Gas Emissions



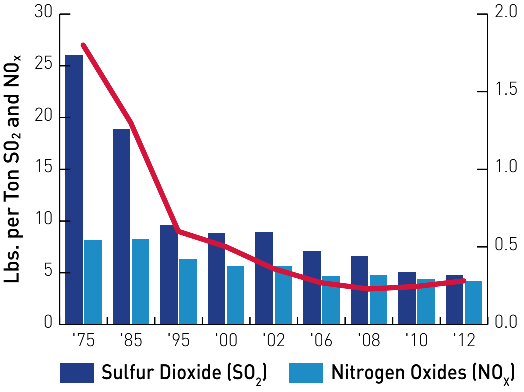
A recent study by the National Council for Air and Stream Improvement (NCASI) shows that the GHG reduction benefits of using biomass residuals for energy by the forest products industry are equivalent to about 218 million tons of carbon dioxide. This is comparable to removing about 40 million cars from the road.

The sustainable management of forests supported by the industry plays a large part in the cycle to offset carbon emissions. In 2011, U.S. forests and wood products captured and stored roughly 16 percent of all carbon dioxide emitted by fossil fuel consumption in the United States.

Air Emissions

EPA's Clean Air Act initiatives have been the focus of AF&PA policy advocacy for the last several years. Some of the emission standards are still not finalized and may not be for several more years. AF&PA members, nonetheless, are continuing to reduce their air emissions. For example, in 2012, sulfur dioxide emissions were 27.4 percent lower than in 2008 due to changes in our fuel mix and continual environmental improvement, and nitrogen oxide emissions were 12.3 percent lower than in 2008.

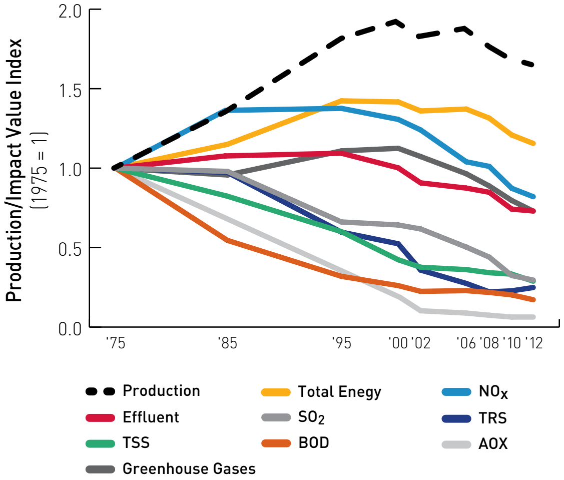
Pulp and Paper Mill Air Emissions



Producing More with Less Environmental and Energy Impact

The result of our sustainable manufacturing efforts has been a "decoupling" over many years of our environmental and energy footprint from our levels of business activity and production. Advances we made in reducing environmental and energy impacts were "decoupled" from the amount of product we produced. The trend plot above shows that while we generally continue to reduce emissions and energy use on a percentage basis (and in some cases, significantly so), as we get closer to background levels of emissions it becomes much more challenging and costly to achieve continued reductions.[8] Appendix I of this report compiles all the environmental metrics on which we are reporting our progress.

Producing More with Less Impact



Sustainability Award Winner

KapStone's Longview Mill received the 2013 AF&PA Leadership in Sustainability Energy Efficiency/Greenhouse Gas Reduction Award for reducing greenhouse gas emissions by 72 percent over the last decade; reducing overall energy use by 37 percent since 2007; reducing overall energy used per ton of paper produced by 17.6 percent since 2007; and increasing total tons of paper produced by 50 percent since 2006.

Paper Recovery for Recycling

Industry-led efforts to increase paper recovery are among the best examples of how we are protecting our environment and preserving and growing the economic contributions of the industry and its businesses. Our industry's 2013 paper recovery rate is 63.5 percent, and we have exceeded 60 percent recovery for the past 5 years. Our goal is to exceed 70 percent recovery by 2020. The amount of paper recovered for recycling has increased by more than 70 percent since our industry committed to setting and achieving recovery goals in 1990. Paper recovery is important to the U.S. economy; it is a success because it is voluntary and market-driven.

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[8] Pollutant and energy consumption data have been extrapolated from reporting AF&PA member companies to the entire industry by multiplying weighted average per ton intensities of reporting companies by industry level production.

AF&PA Outreach

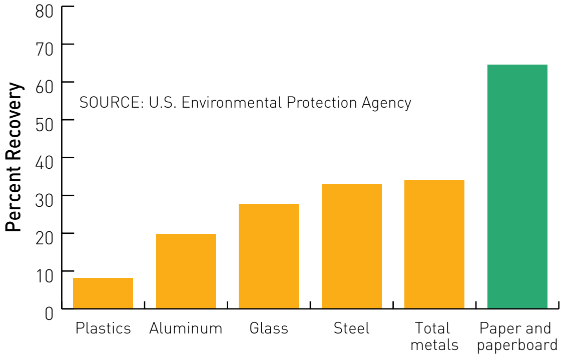
RecycleMania, an annual eight-week competition for colleges and universities, engaged 461 schools across the U.S. and Canada — collecting 89.1 million pounds of recyclables and organic materials. Rutgers, the United States Military Academy, Antioch University, Kalamazoo College and Valencia College were the top award winners. The 2014 competition is sponsored by AF&PA, Alcoa Foundation, the Coca-Cola Company, and SCA. The collection of recyclable materials by contestants prevented the release of 126,597 metric tons of carbon dioxide equivalents.

Paper recovery for recycling extends the useful life of fiber. Approximately 78 percent of all U.S. paper mills use some recovered fiber to make everything from paper-based packaging to tissue to office paper and newspaper.

The paper industry's recycling success leads the way for all other U.S. recycling efforts and also keeps paper out of landfills. Approximately 2.5 times more paper is recycled than is sent to landfills, and every ton of paper recovered for recycling saves 3.3 cubic yards of landfill space. According to the U.S. Environmental Protection Agency (EPA), only 27.7 percent of glass, 19.8 percent of aluminum, and 8.8 percent of plastics consumed were recovered for recycling in 2012, compared to 64.6 percent of paper.

Paper recovery for recycling is also widely accessible: In 2010, 87 percent of Americans had access to community curbside and/or drop-off paper recycling.

2012 Paper Recycling vs. Other Materials



AF&PA member companies' use of recovered fiber resulted in avoided greenhouse gas emissions of nearly 18 million metric tons of CO_2 equivalents in 2013. This has the added benefit to society of reducing other air pollutants that would be released if the paper were to end up in a landfill.

To help educate students and their families about the importance of paper recycling, AF&PA partners with Kaleidoscope to deliver standards-based curricula straight to the classroom. Further, the AF&PA Recycling Awards recognize outstanding paper recycling programs in three categories: Business, Community and School. This year, the program was redesigned to reflect the diversity of paper recycling programs across the country. In each category, there are prizes for creativity, participation, partnerships, and volume of paper collected.

This year's winners in each category are:

Creativity — unique and innovative ways that have been used to market the program, raise awareness and generate interest

- *Community*: Township of Nutley (Nutley, NJ)
- *School*: Greenhill School (Addison, TX)
- *Business*: Michael Dunn Center (Kingston, TN)

Participation — unique and innovative ways successful programs increased participation and tonnage collected

- *Community*: Vance Air Force Base (Enid, OK)
- *School*: Damascus Elementary School (Salem, OH)
- *Business*: Michael Dunn Center (Kingston, TN)

Partnerships — innovative partnerships (community, business, non-profit organizations) used to promote increased recovery

- *Community*: Metro Waste Authority (Des Moines, IA)
- *School*: Ocosta High School (Westport, WA)
- *Business*: Michael Dunn Center (Kingston, TN)

Volume — total amount of paper and paperboard collected

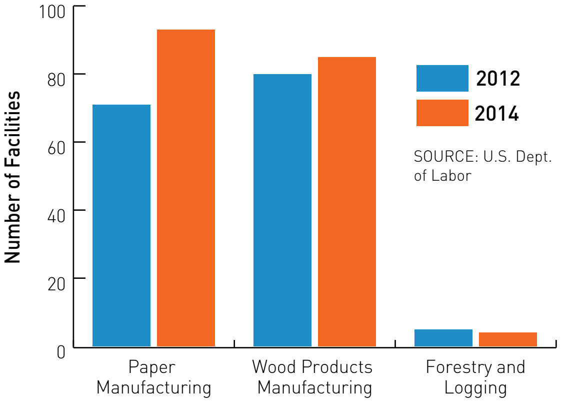
- *Community:* Township of Nutley (Nutley, NJ)
- *School:* Damascus Elementary School (Salem, OH)
- *Business*: Curly's Foods, Inc. (Sioux City, IA)

People

Worker Safety

Because any injuries to our employees are not acceptable, we are continuing to work toward our vision of zero injuries for the industry. Our members continue to look for innovative worker safety programs to realize this vision. Members have increased their participation in the OSHA Voluntary Protection Programs (VPP). Program members are industrial facilities that voluntarily work to maintain job illness and injury rates below national Bureau of Labor Statistics averages.

Member VPP Enrolled Facilities



SOURCE: U.S. Dept. of Labor

AF&PA Sustainability Award Winner

International Paper received the 2012 AF&PA Leadership in Sustainability Safety Award for the "It's about...LIFE" campaign. After the campaign was launched in 2010, Life-changing Injuries and Fatality Elimination (LIFE) were reduced across the company. Along with five specific areas of focus, LIFE put a face to safety with its "This is Why I Work Safe" toolkit, video and website, asking employees to bring photos of loved ones into their workplace as a constant reminder to work safely.

Communities

AF&PA member companies remain a vital source of skilled jobs in rural communities throughout the U.S. More than 75 percent of U.S. pulp and paper mills are located in counties designated by the U.S. Census Bureau as more than 80 percent rural. A majority of the workers employed in the forest products industry possess at least a high school diploma (or equivalent).[9] Member companies provide training to their employees either through on-the-job training programs or by providing the opportunity for employees to take courses at local colleges or universities to improve their skill base.

In anticipation of the need for highly skilled and specialized workers, member companies have engaged educational institutions to ensure that future

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[9] Source: Employment Projections Program, U.S. Department of Labor, U.S. Bureau of Labor Statistics.

employees have the appropriate skills and vocational training.[10] This support has come through donations to university programs, partnerships with local high schools or universities to provide internship opportunities, mentoring programs, and engagement in the development of curricula and classes that will provide graduates with the proper skill set to succeed in the job market.

Member companies also are involved in projects and programs to enhance the well-being of the communities in which they operate. These programs include watershed cleanups, recycling drives, and forest restoration and regeneration. Some programs are yearly events to help beautify a watershed or neighborhood. Others are programs that have both social benefits for the community and benefit the economics of the company, e.g., recycling drives provide companies that manufacture recycled paper products with raw materials, and conservation projects ensure the long-term viability of the forests that provide the raw material for virgin pulp.

AF&PA Member Case Studies

Sappi Fine Paper pledged $250,000 for three initiatives to support Science, Technology, Engineering and Math (STEM) and other education programs at targeted colleges and universities near company mills.

Sonoco has committed $5 million over five years to fund Partners for Unparalleled Local Scholastic Excellence (PULSE), a public/private partnership to expand student development and curriculum opportunities through collaborative academic and social development initiatives, focused on schools located in the company's hometown of Hartsville, South Carolina.

Building the Bio-based Economy

According to the U.S. Census Bureau, the world population will exceed 9 billion by 2050. All these people will have needs — many of which can be filled by forests. Forests are incredibly rich and complex ecosystems, delivering services that are necessary for human well-being and survival — like fresh water, food, and shelter. Many industries depend on forests for their resources, not just the forest and paper industry.

Bio-based products already help meet the growing global demand for a wide range of existing and new sustainable products. Pulp is used in items as diverse as sanitary products, like diapers and feminine care products; tissue products, such as napkins and wipes; electronics, including the flat screens of televisions and laptops; and car tires.

For decades, the pulp and paper industry also has produced ingredients used in detergents, cleaning aids, asphalt emulsifiers, ink resins, and oil drilling fluids as valuable co-products of papermaking. Extractives in wood include resins and fatty acids that are recovered in the pulp mill, thereby avoiding their release into the atmosphere or surface waters. The recovered components are separated and converted into products tailored to specific market needs. Making these products makes pulp and paper mills more sustainable and supplies green chemicals to global markets.

Through nanotechnology, which manipulates matter on an atomic and molecular scale, scientists are looking into ways that trees can improve the sustainability of existing paper-based products as well as deliver a new generation of sustainable products, including high-tech materials that are only beginning to be imagined. Wood contains cellulosic nanomaterials that provide strength and stiffness to trees. When isolated, these materials can be used to strengthen other items, such as plastic fiber-reinforced composites.

Forest biomass is increasingly becoming an important feedstock for green chemicals. Technologies to convert the sugar-based carbohydrates in wood and the building blocks in lignin to a wide range of plastics and chemicals that now are made from fossil fuels are available, and more efficient methods are under development. The sustainability initiatives of many chemical companies, including several that supply essential raw materials for papermaking, are encouraging new efforts to make chemicals from renewable resources such as wood.

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[10] According to a survey conducted by McKinsey & Company, a consultancy, 45 percent of employers in the U.S. believed that there was a lack of skills among graduates, which led to vacancies in entry-level positions. (McKinsey Center for Government, *Education to Employment: Designing a System that Works*).

Part Two

Performance Tracking: The Statistics of Sustainability

AF&PA's ambitious *Better Practices, Better Planet 2020* initiative includes one of the most extensive collections of quantifiable goals for a major U.S. manufacturing industry. We are proud to report that AF&PA members are on track to meet our 2020 sustainability goals, based on the following 2012 calendar year performances (except for recovery for recycling, which is the 2013 rate).[11]

- **Increase paper recovery for recycling:** Currently at 63.5 percent, we have exceeded 60 percent recovery every year since 2009.
- **Increase energy efficiency:** We are more than three-quarters towards meeting our energy efficiency goal to reduce our use of purchased energy by 10 percent between 2005 and 2020. AF&PA members' purchased energy use is currently just 11.8 million BTUs per ton of production,[12] an 8.8 percent reduction from 2005 levels.
- **Reduce greenhouse gas emissions:** AF&PA mills have come very close to achieving the goal to reduce greenhouse gas emissions by at least 15 percent by 2020. Emission rates in 2012 were 14.5 percent lower than those in 2005.
- **Promote sustainable forestry:** Companies continue to seek to increase fiber procured from both third-party certified forestlands and through certified fiber sourcing programs. In 2012, the percentage for each of these wood fiber sources was 29 and 95, respectively, both of which are increases from the 2005 baseline. We are continuing to work with governments and other stakeholders to combat illegal logging.
- **Strive for the safest possible workplace:** Because injuries to our employees are not acceptable, we established a vision for the industry of zero injuries. We are measuring progress toward that vision by setting a goal to further improve our safety incidence rate by 25 percent from 2006 to 2020. AF&PA member companies have reduced their recordable case incidence rate by 24 percent since 2006.
- **Reduce water use:** Member pulp and paper mills are working to reduce water use by 12 percent by 2020. Currently, mills report using 6 percent less water than in the 2005 baseline year.

Reporting Our Progress

AF&PA and its predecessor organization, the American Paper Institute, have tracked paper product production and industry economic performance for decades. Over that time, the paper and wood products markets have grown more global. Consequently, our industry's sustainability depends on our ability to successfully compete in those global markets, increasing the importance of the social and economic metrics, along with the environmental metrics.

Setting relevant and challenging goals is another important step in the sustainability pursuit. AF&PA's first goal, set in 1990, was to achieve a 40 percent paper recovery rate by 1998. This goal was achieved four years early, and a new 50 percent recovery goal was established. After achieving that goal in 2003, two successively higher goals were set — and achieved — before the decade was out. AF&PA's current suite of six goals, established in 2011 through the *Better Practices, Better Planet 2020* program, continues to seek increased paper recovery rates in addition to

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[11] Except for the recovery for recycling and safety goals, all numeric goals use a 2005 baseline year. The 2005 baseline is derived from the averaging of 2004 and 2006 data as reported by member companies through our regular biennial data collection process. The recovery goal does not have a baseline, and the safety goal baseline is 2006. Production-based statistics quoted in this report refer only to quantities of pulp, paper, and primary wood products produced. They do not include converted paper or fabricated wood products.

[12] Wood products generally require significantly less energy to manufacture than pulp and paper products. Such differences can distort energy efficiency comparisons if there are major changes in the paper-wood production mix, as occurred between the 2005 base year and 2010, when wood's share of the production mix declined significantly. Thus, the 2005 production mix between wood and paper has been adjusted to be the same as it was in 2010 to ensure a more representative comparison of energy efficiency performance, and we will be using this same 2010 mix in 2012 and in future years.

improved energy efficiency, reduced greenhouse gas emissions, improved sustainable forestry practices, better workplace safety, and reduced water use.

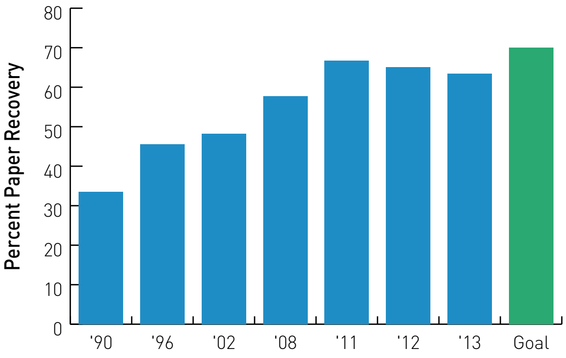
Our progress towards meeting these goals is reported here. Trends associated with all of the other sustainability indicators on which we are reporting are included in the Appendix that follows.

Increase Paper Recovery for Recycling

GOAL: Exceed 70 percent rate of paper recovery for recycling by 2020

U.S. paper recovery has increased by more than 70 percent since 1990 due to the efforts of the industry and the millions of Americans who recycle every day. Recovering valuable resources extends the fiber supply, allowing our industry to reuse its products to make new ones. In addition, paper recovery saves landfill space — an average of 3.3 cubic yards of landfill space is saved for each ton of paper recycled. U.S. paper recovery exceeded 60 percent for the past 5 years, reaching 63.5 percent in 2013. Paper recovery is a success because it is voluntary and market-driven. Recovered paper markets are driven by the same supply-demand dynamics that characterize the broader economy. Recovered paper that was sorted or processed in the U.S. had a 2012 market value of $8.4 billion. The value of U.S. recovered paper exports totaled $3.1 billion in 2013. Paper recovery has fostered a dynamic marketplace that allows recovered fiber to find its highest-value end. That, in turn, helps to encourage more recycling.

Progress Toward Recycling Goal



Sustainability Award Winner

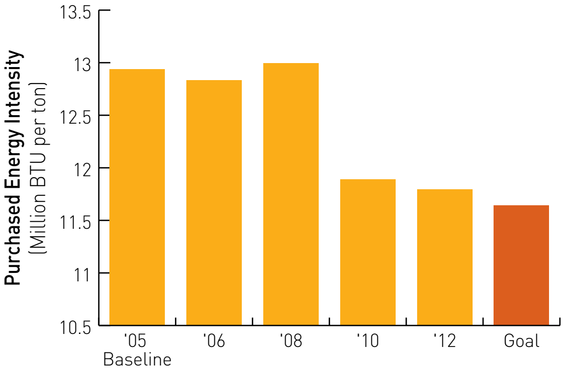
A unique partnership between **RockTenn** and a customer created sustainability awareness and increased recycling through an employee education program that focused on disposal decisions and removal of recyclables from the waste stream. The initiative resulted in 61.6 percent of the customer's waste stream being recycled and reduced waste management expense by 16 percent. The program received a 2013 Leadership in Sustainability Paper Recovery for Recycling Award from AF&PA.

Improve Energy Efficiency

GOAL: Improve members' purchased energy efficiency use by at least 10 percent from 2005 to 2020

Energy generation and use at AF&PA member mills is an exciting success story. Purchased energy use in 2012 was 11.8 million BTUs per ton of production against a goal of 11.6 million BTUs per ton. Improving our industry's energy efficiency in purchased energy allows us to produce more with less, leaves more natural resources for future use, and saves resources, which helps to keep and create jobs. Improved energy efficiency has led to a reduction in purchased energy of 8.8 percent compared to the 2005 baseline of 12.9 million BTU per ton of production.

Progress Toward Energy Goal



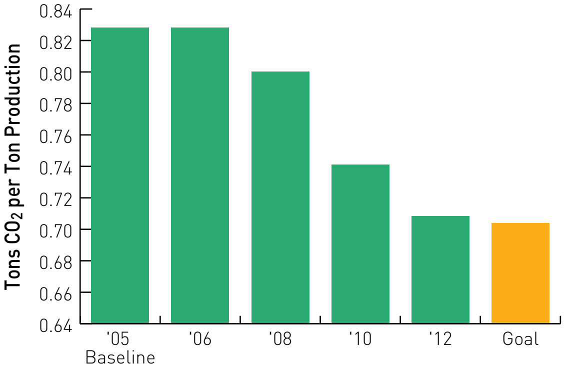
Reduce Greenhouse Gas Emissions

GOAL: Reduce our members' greenhouse gas emissions by at least 15 percent from 2005 to 2020

In 2012, AF&PA members came close to achieving the 15 percent greenhouse gas (GHG) reduction goal. Emissions were 0.709 tons of CO_2 equivalents per ton of production versus a goal of 0.704. This amounts to a decrease of 14.5 percent from the 2005 baseline. Reducing our members' greenhouse gas emissions is part of a global environmental effort. It is closely related to other AF&PA sustainability goals. Recovering paper for recycling keeps paper out of landfills — where it releases GHGs when it decomposes — and improving energy efficiency leads to fewer GHG emissions resulting from the manufacturing process.

Reliance on carbon-neutral biomass derived energy, improvements in energy efficiency, and increases in paper recovery for recycling have all contributed to this reduction. Additionally, promotion of sustainable forestry can increase carbon storage in the managed

Progress Toward Greenhouse Gas Reduction Goal



forests that provide raw materials for our mills. In 2011, U.S. forests and wood products captured and stored roughly 16 percent of all carbon dioxide emitted by fossil fuel consumption in the United States.

Promote Sustainable Forestry

GOAL: Increase the amount of fiber procured from certified forestlands or through certified fiber sourcing programs in the U.S. from 2005 to 2020 and work to decrease illegal logging

All AF&PA members that own forestland are required to conform to a credible forest management program. These credible certification programs include the Sustainable Forestry Initiative® (SFI®), the Forest Stewardship Council (FSC®) program, the American Tree Farm System (ATFS), and the Programme for the Endorsement of Forest Certification (PEFC™)-endorsed programs. In 2012, 29 percent of member fiber was procured from certified forestlands, and 95 percent was procured through certified fiber sourcing programs, both of which are increases from the 2005 baseline.

Individual member companies work diligently to safeguard against procurement of fiber from illegally-logged sources. Illegal logging contributes to global deforestation and climate change, threatens many species with extinction, denies forest-dependent communities access to resources, and undermines legitimate businesses. Companies identify and document sources, require suppliers to sign agreements, use third-party certification of chain-of-custody records, and can conform to sustainable fiber sourcing standards to help in achieving this goal.

Sustainability Award Winner

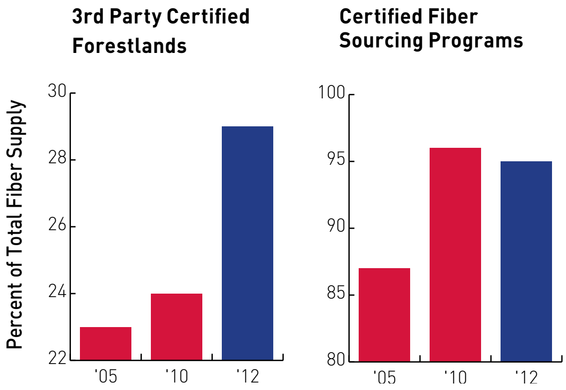
Through its "Climate Leadership Initiative," **International Paper** aggressively managed and reduced greenhouse gas emissions at its facilities by 40 percent from 2000 to 2011 through investments in capital projects and increased manufacturing efficiencies, new technologies, and encouraging employees to find new ways of working. The company was recognized by AF&PA, through a 2012 Leadership in Sustainability Energy Efficiency/Greenhouse Gas Reduction Award, and by the U.S. Environmental Protection Agency for its achievement.

AF&PA and its members support and promote efforts to reduce illegal logging in a number of ways. In the U.S., that effort has centered on the implementation of the 2008 Lacey Act amendments, which are helping transform the global marketplace. Those amendments serve to increase transparency and due care, shifting supply chains towards legally-sourced product. AF&PA members are finally able to compete on a more level playing field, and countries and businesses are becoming much more aware and concerned about the legality of their sourcing practices, which helps support good forest governance efforts. Anecdotal information indicates that more and more customers in major wood markets are seeking legal sources of wood and are avoiding sources of wood of questionable origin.

The Lacey Act and other U.S. efforts to curb illegal logging have gained traction; the European Union and Australia both have implemented their own laws to address the illegal timber trade and to encourage trade in legally sourced wood and plant products. However, this shift is far from complete, as illegal logging remains a serious problem in many parts of the globe.

AF&PA and its members are actively promoting measures to maintain the integrity and effectiveness of the amendments. For instance, we have advocated for adequate funding in the federal budget for agencies involved in the implementation and enforcement of the Lacey Act. We also worked with our allies against legislative efforts to reduce the effectiveness of the 2008 Lacey Act amendments. Finally, we have supported provisions in free trade agreements being negotiated by the U.S. government intended to curb illegal logging and associated trade.

Progress Toward Sustainable Forestry Goal

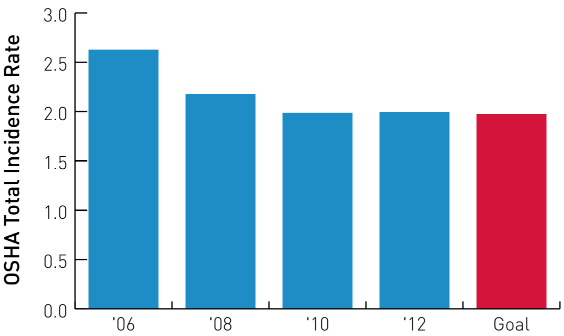


Strive for the Safest Possible Workplace

GOAL: A vision for the industry of zero injuries and measuring progress toward that vision by further improving our incidence rate by 25 percent from 2006 to 2020

The safety of our industry's employees is a priority of our sustainability program, critical to both employee well-being and the success of our businesses. The Occupational Safety & Health Administration (OSHA) recognizes industrial facilities that implement enhanced safety programs and maintain on the job injury and illness rates below national Bureau of Labor Statistics averages for their respective industries. This recognition includes enrollment in OSHA's Voluntary Protection Programs (VPP). The forest products industry has consistently had the second largest number of facilities of any sector registered by VPP. Because any injuries to our employees are not acceptable, we are continuing to work toward our vision of zero injuries for the industry. AF&PA member-implemented worker training initiatives, increased automation, and a host of injury preventive measures and safeguards have resulted in a recordable case incidence rate reduction of 24 percent since 2006. AF&PA's mandatory Environment, Health & Safety Principles require that members have health and safety policies in place and that the companies perform frequent safety audits. Our members continue to look for innovative worker safety programs to realize our vision of zero injuries.

Progress Toward Safety Goal



Sustainability Award Winner

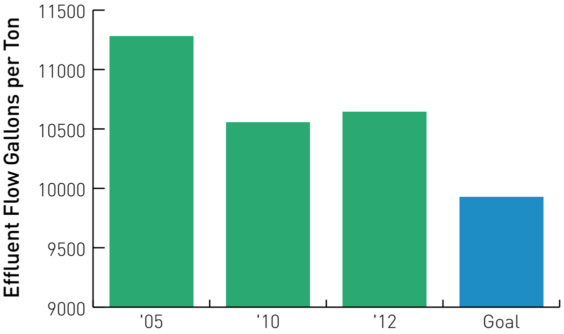
Domtar received the 2013 Leadership in Sustainability Safety Award for its Hazard Mapping Program at a large mill in Alabama. The company worked with the United Steelworkers Union to bring the Hazard Mapping Program to the mill. The mill was systematically mapped to rate hazards: checklists were developed as well hazard identification symbols. In response, 324 hazards were eliminated and, in the second year, the recordable incident rate was 1.07.

Reduce Water Use

GOAL: Reduce water use in members' pulp and paper mills by 12 percent from 2005 to 2020

Reducing water use in the paper manufacturing process is responsible stewardship of an important local resource. Just like trees, water is a valuable natural resource that our industry strives to manage in a sustainable manner. Water sustainability is achieved, in part, through water reuse and recycling. Because effluent measurements are precise and can be accurately and transparently reported, they serve as the surrogate measure of our water withdrawals. Since 2005, AF&PA member paper mills have reduced water use by 6 percent. AF&PA members continue to seek ways to reduce water use, increase water reuse and recycling, and disseminate information about the role of water in our industry.

Progress Toward Water Goal



BETTER PRACTICES
BETTER PLANET 2020
Continuing AF&PA's Commitment to Sustainability

The AF&PA Sustainability Award Winners 2012-13

2012

Leadership in Sustainability – Energy Efficiency/ Greenhouse Gas Reduction (Large Company)

Georgia-Pacific
Improving Energy Efficiency

International Paper
Climate Leadership Initiative

Leadership in Sustainability – Energy Efficiency/ Greenhouse Gas Reduction (Small Company)

Expera Specialty Solutions
(formerly Thilmany Papers)
Energy and Water Restructuring Program

Leadership in Sustainability – Safety

International Paper
It's about...LIFE

Leadership in Sustainability – Water

MWV
Mahrt Mill Water and Energy Reduction Project

Innovation in Sustainability

Green Bay Packaging
Fiber Reclaim Project

2013

Leadership in Sustainability – Energy Efficiency/ Greenhouse Gas Reduction

KapStone Paper and Packaging Corporation's Longview Mill
A One-Year Snapshot of Longview's Multi-Year Journey

Leadership in Sustainability – Paper Recovery for Recycling

RockTenn
RockTenn & Customer Recycling and Waste Reduction Initiative

Leadership in Sustainability – Safety

Domtar
Hazard Mapping at Ashdown

Leadership in Sustainability – Sustainable Forest Management

Domtar
Four States Timberland Owners Association

Leadership in Sustainability – Water

Georgia-Pacific Brunswick Cellulose Operation
Water Use Reduction Project

Innovation in Sustainability

Graphic Packaging International
Tite-Pak® Innovation Beverage Packaging

Appendix One:

Results from AF&PA's 2012 member survey regarding economic, social, and environmental sustainability indicators, plus information from government sources.

The Economic Indicators of Sustainability

Employment Trends

The forest products industry makes substantial contributions to global, U.S., and, especially, local economies. Pulp, paper, paper converting, and wood products manufacturing plants are major employers. In all, the sector currently employs nearly 900,000 people and is among the top 10 manufacturing employers in 47 of the 50 states.

Although employment in the sector declined sharply in 2008 (8.1 percent) and 2009 (15.8 percent), the rate of decline decreased substantially in 2011 (1.8 percent) and 2012 (0.6 percent). Preliminary data from the Bureau of Labor Statistics suggest that forest products industry employment rose 2.3 percent in 2013. Much of this rebound occurred at wood products plants. At pulp, paper, and paperboard mills, employment stood at about 108,000 people in 2012. This compares to 132,000 in 2007, one year prior to the start of the recession.

Labor Productivity

The forest products industry must operate in a highly competitive world marketplace. Improving worker productivity is an important part of the drive to reduce production costs. Output per man-hour at pulp, paper, and paperboard mills increased 36 percent during the ten-year period 2001 through 2011. The average annual increase for the period was 3.1 percent. At wood products facilities during the same period, labor productivity rose 23 percent, or at an average rate of 2.1 percent per year. The productivity contributions of our workers are critical to the U.S. industry's ability to compete in the world marketplace.

Forest Products Industry Labor Productivity Gains

SOURCE: U.S. Bureau of Labor Statistics

Compensation

The forest products industry provides skilled jobs paying high wages. According to data compiled by the Bureau of Labor Statistics (BLS) and the Bureau of Economic Analysis, total compensation for the sector in 2012 was approximately $52 billion. These sectors include pulp, paper, and paperboard mills, paper converting, wood products mills, wood kitchen cabinets, and logging.

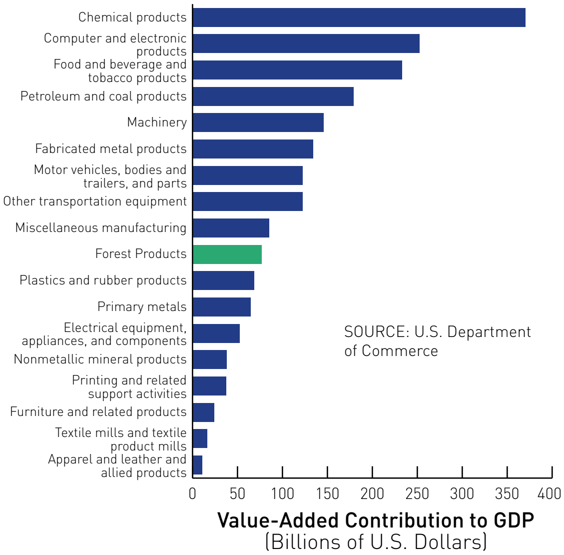
Contribution to Gross Domestic Product (GDP)

In 2012, the forest products industry contributed almost 4 percent of the U.S. manufacturing GDP, according to Census Bureau data. Pulp, paper, and paperboard contributed 2.6 percent and wood products, 1.2 percent.

Production

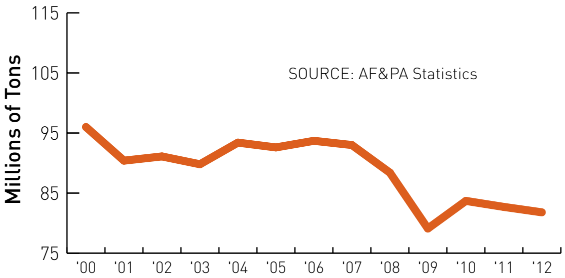
U.S. paper and paperboard production fell sharply during the recession years, declining 4.9 percent in

Forest Products Industry Contribution to U.S. Manufacturing GDP (2012)



SOURCE: U.S. Department of Commerce

Paper Industry Production



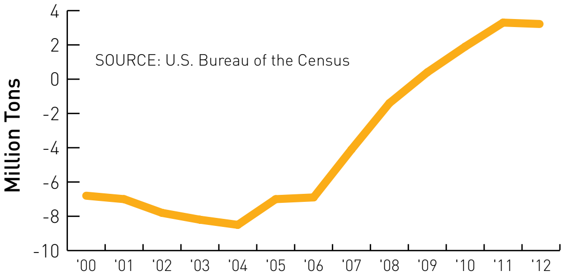
SOURCE: AF&PA Statistics

2008 and 10.6 percent in 2009. Though declines have continued, they have been much smaller in recent years. Production was off 1.1 percent in 2012 and, according to preliminary data, 0.8 percent in 2013.

U.S. Trade Competitiveness

The U.S. has traditionally run a trade deficit with respect to paper and paperboard. That deficit reached 8.5 million tons in 2004 and then began to contract. The U.S. recorded a small trade surplus with respect to paper and paperboard in 2009, which continued to grow to reach 3.2 million tons in 2012.

Paper Industry Trade Balance Improvement

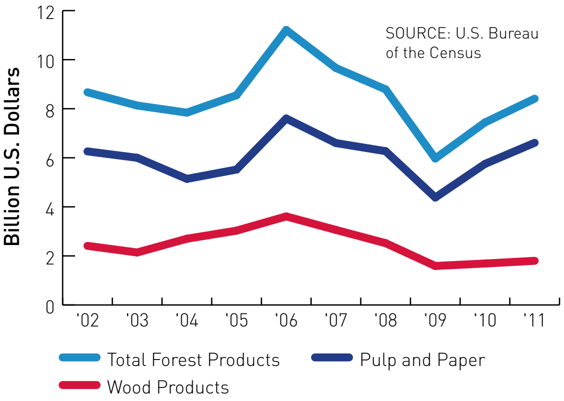


SOURCE: U.S. Bureau of the Census

Capital Expenditures

Forest products industry capital expenditures fell from $11.2 billion in 2006 to $6.0 billion in 2009 before beginning to rebound. They reached $7.4 billion in 2010 and increased further to $8.4 billion in 2011, the latest year for which data are available. The 2011 level of expenditures was on par with average forest products industry capital spending of $8.5 billion a year for the period 2002 through 2011. In 2011, paper and paperboard mills spent $6.6 billion on plant and equipment, while wood products facilities spent $1.8 billion.

Forest Products Industry Capital Expenditures



SOURCE: U.S. Bureau of the Census

AF&PA Member Case Study

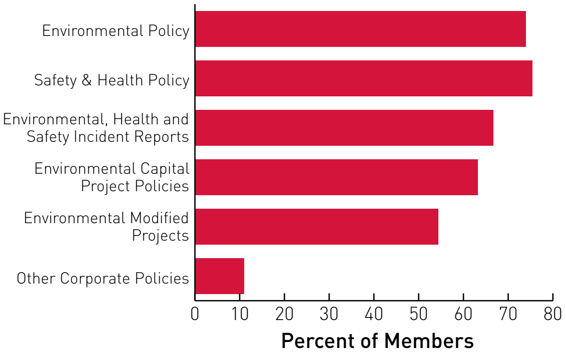
Employees at **Clearwater Paper Corporation**'s Shelby, North Carolina, mill partnered with Communities in Schools to provide backpacks for hundreds of school children in need.

The Social Indicators

Individual Member Policies

Members adhere to AF&PA EHS policies in a variety of ways. These can include formal written internal policies, agreements with employees and other stakeholders, incorporation of principles in meetings and training programs, etc. Safety and health policies were reported by 75.4 percent of members; environmental policies by 73.7 percent. In addition to EHS policies, members also have policies for reporting EHS incidents to senior management, highlighting the need for environmental capital projects, use as

Members Reporting Internal Policies

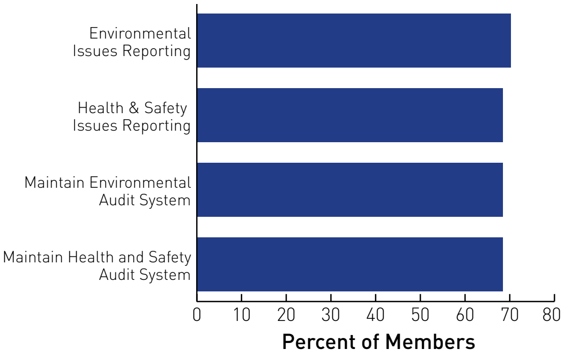


guidance regarding environmentally-oriented product design, and other proclamations (social responsibility policies, stewardship measures, sustainability policy statements, etc.) during 2012.

Internal Reporting

Members establish internal reporting systems to inform senior management, middle management, and line employees of the company's sustainability performance and trends. Details regarding these systems vary member to member but are guided by the AF&PA EHS Principles. Environmental issues reporting systems were recorded by 70.2 percent of members in the 2012 survey. Health and safety reporting systems were recorded by 68.4 percent, while the same number of members also reported having audit systems in place for both health and safety and environmental programs.

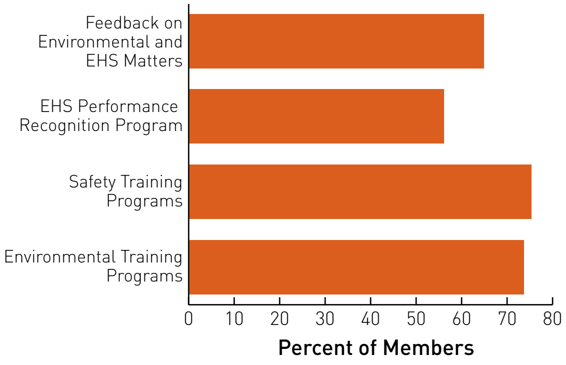
Members Internal Reporting Systems



Employee Programs

Company programs include several measures that aid and encourage employees to follow sustainable practices. These include environmental and safety training programs, employee recognition programs, and confidential feedback arrangements employees can use to report any problematic safety or environmental performance practices that they encounter on the job. In response to the 2012 survey, AF&PA members reported that 73.7 percent utilized environmental training programs, 75.4 percent utilized safety training programs, 56.1 percent sponsored EHS employee performance recognition programs, and 64.9 percent provided employee feedback mechanisms regarding environmental and safety matters.

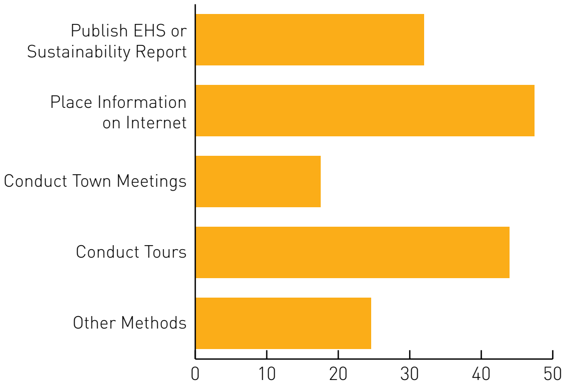
Employee Sustainability Program Measures



Public Reporting

AF&PA members strive to keep stakeholders informed of their sustainability activities through public engagement initiatives. Such initiatives include published reports, Internet postings, town hall meetings, plant tours and other means. Many members use a mix of methods. In 2012, 32 percent of members published EHS or sustainability reports. Nearly half (47.4 percent) made information regarding sustainability performance available on the Internet. Town meetings were held by 17.5 percent, while 43.9 percent conducted plant tours and 24.6 percent used other means for public reporting such as newsletters and newspaper articles, responses to direct stakeholder inquiries, cooperation with trade organizations, and presentations to local civic organizations.

Members Public Engagement Reporting

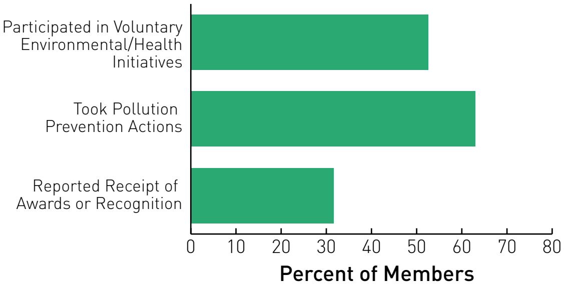


Voluntary Efforts, Pollution Prevention, and External Recognition

AF&PA members actively participate in voluntary pollution reduction and pollution prevention initiatives. Examples include the U.S. EPA's Energy Star program, U.S. EPA's Climate Leadership program relating to greenhouse gas emissions reductions, and others. In response to the 2012 EHS member survey, AF&PA members reported on participation in voluntary environmental and health-related programs and on initiatives taken in the area of pollution prevention. Members also received recognition for their environmental and sustainability accomplishments from outside organizations and officials. Examples of these awards and recognition include:

- Energy excellence awards from public utilities;
- Safety awards from state departments of labor officials and/or governors;
- Awards and recognition from universities;
- Awards and recognition from customers and/or supply chain organizations; and
- Environmental sustainability awards from AF&PA and other associations.

Voluntary Efforts, Pollution Prevention, and External Recognition

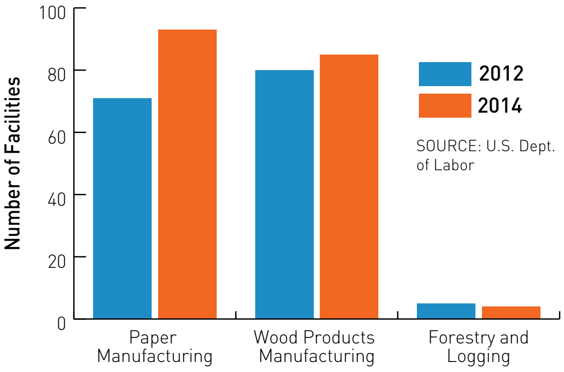


Worker Safety Performance

AF&PA member OSHA incidence rates reported via the EHS Principles Verification Program 2012 Survey show that the number of injury or illness cases per 100 equivalent full-time employees at pulp and paper mills decreased 4.3 percent between 2010 and 2012. However, incidence rates at wood products facilities increased.

The OSHA VPP status is awarded to industrial facilities that voluntarily work to maintain job illness and injury rates below national Bureau of Labor Statistics averages. As of February 2014, AF&PA members had 4 forestry and logging operations, 85 wood products manufacturing plants, and 93 pulp and paper manufacturing facilities awarded VPP status. These numbers compare with 80 wood products plants and 71 pulp and paper facilities recorded in February of 2012. The number of forestry and logging operations recorded as obtaining VPP status was 5 in 2012.

Member VPP Enrolled Facilities



SOURCE: U.S. Dept. of Labor

Public Policy and Community Outreach

It is important for AF&PA member companies to be engaged in the development of public policy and in community outreach. In this way, policymakers have an opportunity to hear directly from regulated entities regarding how proposed policies or regulations will affect the industry. Through collaborative processes they get a better understanding of measures likely to produce the best and most cost-effective results. Community members gain the opportunity to become better informed about local facility operations. They can present their own points of view and concerns, as well as have an opportunity to support the company. Based on the 2012 member survey results, 63.2 percent of members reported conducting public policy and community outreach activities.

The Environmental Indicators

AF&PA members have tracked and worked to reduce releases to the environment for decades. This practice has provided an important database from which our substantial progress towards sustainability can be reported.

Energy Production

Renewable biomass fuels at member mills provided 65.9 percent of energy produced at pulp and paper mills and 70.6 percent of energy produced by wood products facilities. These carbon neutral materials include bark, sawdust, wood shavings, and other woody material collectively known as "hogged fuel," as well as spent pulping liquors.

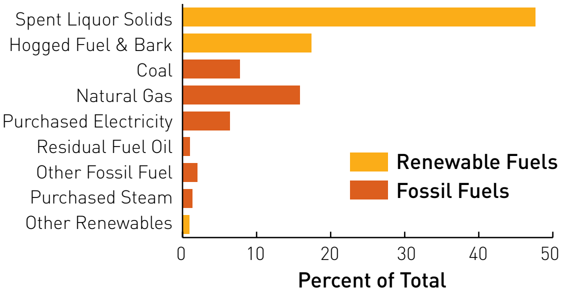
Use of purchased energy (fuels used to produce electricity and steam on-site, as well as steam and electricity purchased directly) at pulp and paper mills has decreased by 44.7 percent since 1972, 25.4 percent since 1990, and 14.6 percent since 2000.

Combined heat and power (CHP) production is an important part of energy generation at forest products manufacturing plants. CHP energy is produced in the forest products industry by utilizing the heat contained in electricity generation turbine exhaust steam in production processes, equipment, and buildings before the condensed steam is returned to boilers for reuse. This process raises the energy production efficiency from 33 percent for non-CHP generation processes to between 50 and 80 percent. In 2012, 96.4 percent of the electricity the industry generated was through CHP, which enabled many members to efficiently generate significant portions of their electricity. Fifty-nine percent of the electricity used by our members was self-generated (the remainder was purchased). Indeed, 42 percent of our members' mills self-generated more than half of their power, and 23 percent sold excess power back to the grid — much of it renewable as well.

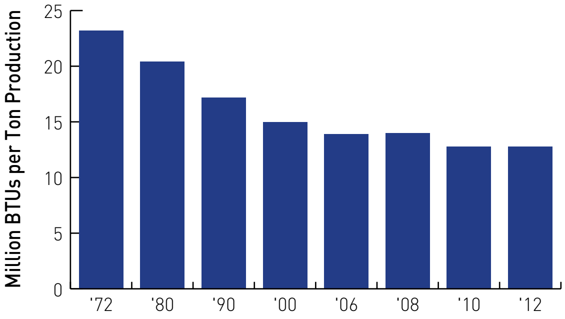
Sustainability Award Winner

Throughout a two-year period, **Expera Specialty Solutions** (formerly Thilmany Papers) completed more than 35 energy-efficiency projects, and its Kaukauna, Wisconsin mill joined the U.S. Department of Energy's (DOE) "Better Buildings Better Plants" program, resulting in a 19 percent reduction in purchased energy intensity. AF&PA awarded them a 2012 Leadership in Sustainability Energy Efficiency/Greenhouse Gas Reduction Award for their accomplishments.

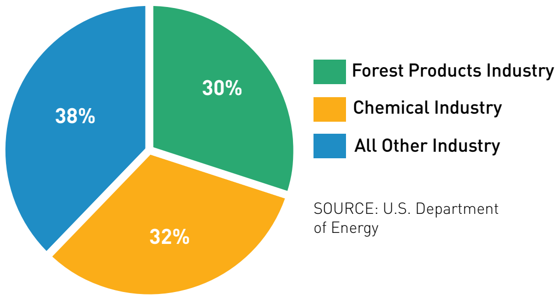
2012 Pulp and Paper Mill Energy Sources



Pulp and Paper Mill Purchased Energy Use



2012 CHP Electricity Generation by Industry



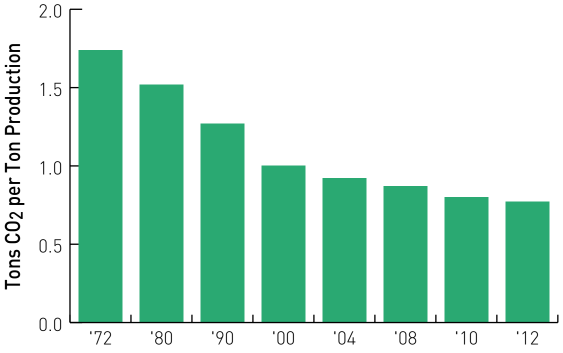
SOURCE: U.S. Department of Energy

The forest products industry is the second largest producer of CHP electricity in the manufacturing sector; only the chemical industry produces more.

Greenhouse Gas Emissions

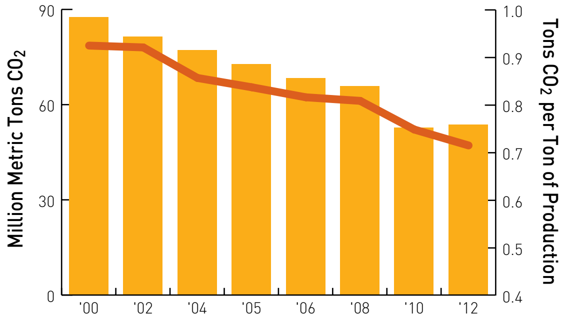
Forest products industry greenhouse gas emissions have been significantly reduced. At pulp and paper mills, the emission rate expressed in tons of CO_2 equivalents per ton of production has been reduced by 55.8 percent since 1972, 23.1 percent since 2000, and 3.9 percent compared to 2010. The absolute emis-

Pulp and Paper Mill Greenhouse Gas Emissions Reductions



Member Greenhouse Gas Emissions

(Total Direct and Indirect)

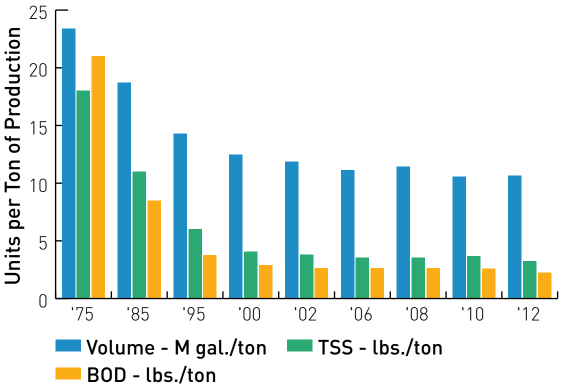


sions from pulp and paper mills and wood products facilities combined, expressed in tons of CO_2 equivalents, have decreased by 38.6 percent since 2000. The emissions intensity rate for pulp and paper mills and wood products facilities combined, expressed in tons of CO_2 equivalents per ton of product, decreased by 22.5 percent since 2000. Between 2010 and 2012, this rate was reduced by 4.4 percent.

Water Discharges

AF&PA member pulp and paper mills utilize sizeable quantities of water in the manufacture of their products. Mills actively seek to employ water conservation and water use reduction practices. Water withdrawn by the mills is recycled and reused up to ten times before being discharged to biological systems for treatment and release back into the environment. Consumptive water use by member mills is low. About 88 percent of water withdrawn for use in the mills is returned after treatment. Since 1975, mills have reduced the quantity of water discharged by 54.5 percent. Since year 2000, water use as measured at the point of release has decreased 14.5 percent. Water use in 2012 was essentially the same as in 2010 — 10,600 gallons per ton of production. Of greater significance is the progress made in effluent quality. Since 1975, the quantity of total suspended solids (TSS) released to receiving waters by mill treatment systems has decreased by 82 percent. Biochemical Oxygen Demand (BOD), a measure of the amount of organic material in the effluent that results in lowered oxygen content of receiving streams, has been reduced by 89.3 percent. BOD reduction since year 2000 is 22.7 percent. Compared to 2010, TSS releases were reduced by 11.5 percent, and BOD releases were reduced by 12.9 percent.

Pulp and Paper Mill Effluent Discharges



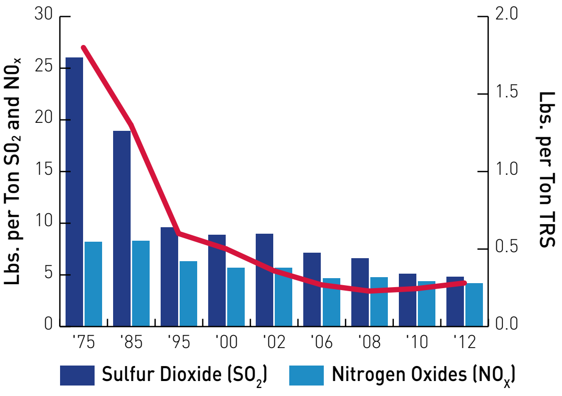
Air Emissions

AF&PA member mills have also substantially reduced air emissions. Releases of sulfur dioxide, nitrogen oxides, and total reduced sulfur compounds at pulp and paper mills have been reduced through process modifications and energy conservation measures. Wood products facilities have reduced nitrogen oxide releases compared to those of the late 1990s. Between 1975 and 2012, paper mill sulfur dioxide emissions have been reduced by 81.6 percent. Since 2000, sulfur dioxide emissions were 46 percent lower. For 2012, sulfur dioxide emissions were 6.4 percent lower than 2010, due to changes in our fuel mix and continual environmental improvement. Nitrogen oxide emissions since 1975 were down 48.9 percent in 2012. Since year 2000, nitrogen oxide emissions have been reduced 26.4 percent. The 2012 emissions of these nitrogen compounds were 3.7 percent lower than 2010. Total reduced sulfur (TRS) compound emissions have been reduced 84.5 percent since 1975 and 44.3 percent since 2000. However, compared to 2010, in 2012 these low level TRS emissions increased by 13.9 percent — from 0.245 pounds per ton to 0.279 pounds per ton.

Sustainability Award Winner

Georgia-Pacific's Brunswick Cellulose, Inc. subsidiary received the 2013 Leadership in Sustainability Water Award for its "Water Use Reduction" project at the Brunswick, Georgia, mill. The mill installed a single-line bleach plant to replace three older pulp bleaching processes, resulting in a reduction in overall groundwater use of nearly 10 million gallons per day, or 30 percent of the mill's total daily use.

Pulp and Paper Mill Air Emissions



Chemical Releases[13]

AF&PA members track and report on chemical releases. Compounds of interest include substances listed by U.S. EPA for reporting through the Toxics Release Inventory (TRI) program and compounds specifically related to operations at pulp and paper mills and wood products facilities. These specific compounds include chlorine, chlorine dioxide, chloroform, and methanol

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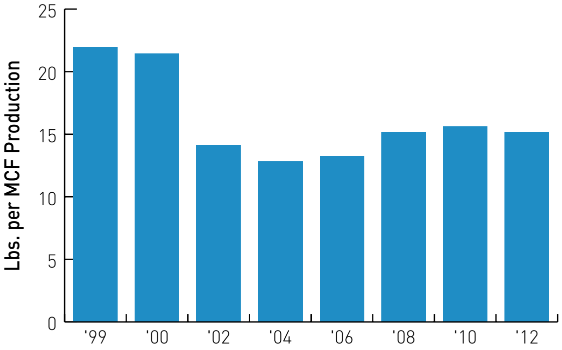
[13] The chemical release data in this section are from the EPA TRI database, except for the pulp mill AOX data, which are from the AF&PA EHS Survey. The data are from AF&PA members only. One factor that makes comparison of these data difficult is that AF&PA membership has changed between these benchmarking years. The membership has not consisted of exactly the same set of mills for each of the comparison years.

Wood Products Facility NO$_x$ Emissions



at pulp and paper mills; methanol and formaldehyde at wood products facilities. Since 1999, pulp and paper mill total TRI releases have been reduced by 28.1 percent. Between 2010 and 2012, total TRI releases increased 16 percent. On a pound per ton of product basis, the reduction between 1999 and 2012 has been 16.6 percent. Between 2010 and 2012, pound per ton release rates increased by 7.5 percent.

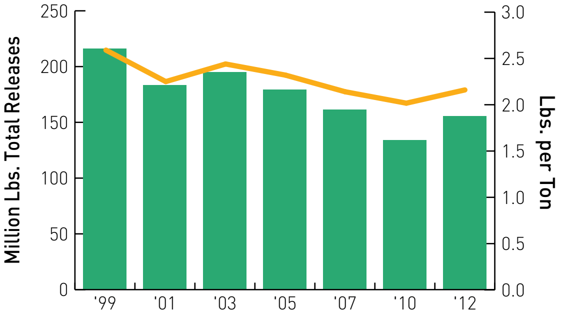
At wood products facilities, TRI total releases have been decreased by 92.2 percent between 1999 and 2012. Between 2010 and 2012, TRI compound total releases decreased 63.2 percent. On a pounds per 1000 cubic feet of product basis, the reductions achieved were 78.6 percent between 1999 and 2012 and 30.4 percent between 2010 and 2012.

Pulp and paper mill releases of chlorine, chlorine dioxide, and chloroform are tracked by looking at total industry release rates as reported by U.S. EPA's TRI Explorer database. Releases of these chlorine compounds have been substantially reduced since 2000. During this period, releases of chlorine have been reduced by 82.6 percent, chlorine dioxide by 32.3 percent, and chloroform by 96.6 percent. Between 2010 and 2012, chlorine releases remained the same at 0.12 million pounds, chlorine dioxide releases increased from 0.40 million pounds to 0.49 million pounds, and chloroform releases decreased 39.3 percent from 0.17 million pounds to 0.10 million pounds.

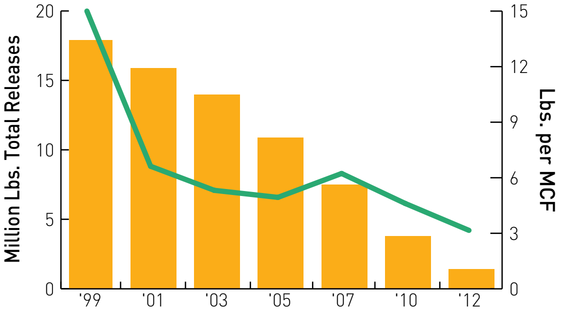
Methanol releases at member pulp and paper mills have been reduced by 33.4 percent between 1999 and 2012. Between 2010 and 2012, methanol releases increased 11.2 percent.

At AF&PA member wood products facilities, methanol releases between 1999 and 2012 decreased by 90.3 percent. Between 2010 and 2012, they decreased by 33.3 percent. Formaldehyde releases decreased by 95.8 percent at wood products facilities between 1999 and 2012. Between 2010 and 2012, formaldehyde releases decreased 50.0 percent, in part because the California Air Resources Board standards, which generally are being met nationally, became effective.

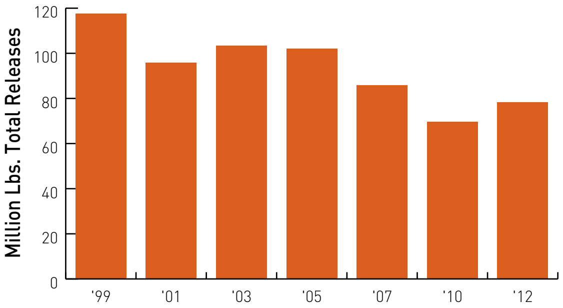
Pulp and Paper TRI Releases



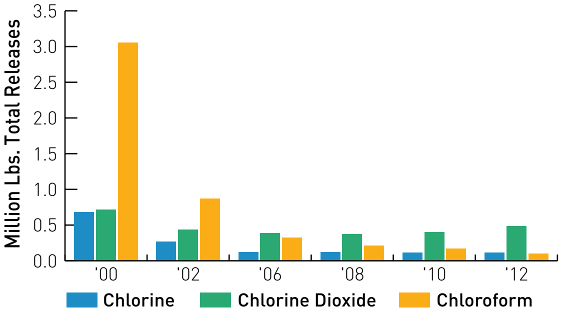
Wood Products TRI Releases



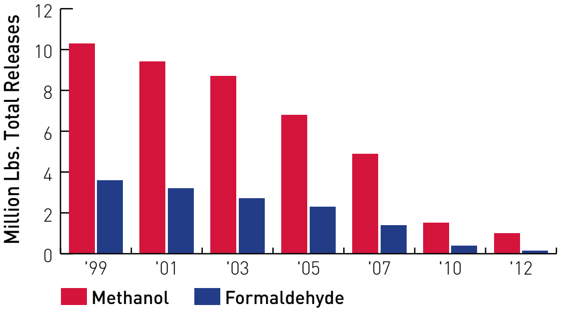
Pulp and Paper Mill Methanol Releases



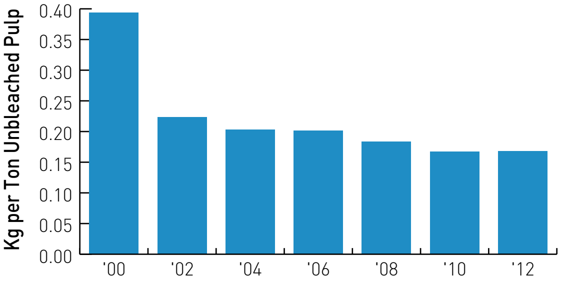
Pulp and Paper Mill Chlorine Compound Releases



Wood Products Facility Methanol and Formaldehyde Releases



Paper Mill Effluent AOX Discharges

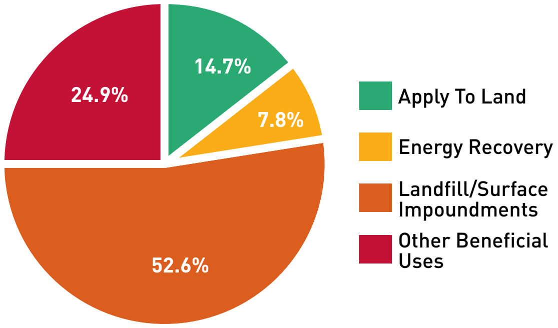


Adsorbable organic halides (AOX) are chlorinated organic compounds that can, under certain conditions, be formed during pulp bleaching. Through process changes, member companies have virtually eliminated AOX releases from pulp mill effluents. Since 1975, AOX releases have been reduced by 95.8 percent and by 57.4 percent since year 2000. Releases recorded in 2012 matched those in 2010, 0.17 kilograms per ton of unbleached pulp.

Beneficial Use of Manufacturing Residuals

Member pulp and paper mills strive to utilize as much raw material brought to the mills as possible. Any materials not utilized for primary products, byproducts, or as primary energy sources are known as manufacturing residuals. These include soil contaminated wood yard wastes, wastewater treatment plant residuals, boiler ash, etc. These materials are beneficially used by spreading on land as soil conditioners and amendments, burned for energy recovery with other biomass fuels, or utilized in other ways. Materials that cannot be beneficially used are placed in landfills or surface impoundments. In 2012, 52.6 percent of generated residuals were disposed in landfills, 14.7 percent land spread, 7.8 percent burned for energy recovery, and 24.9 percent utilized in other ways. In 2012, the portion of residuals disposed in landfills decreased, and beneficial use of these materials increased. In 2010, the residuals portion discarded was 58 percent.

Pulp and Paper Mill Residuals Management



Research, Development and Innovation

AF&PA members utilize many technical resources as they seek continued improvements in process efficiency, product quality, and sustainability. In responses to the 2012 EHS Principles Verification Program Corporate survey, AF&PA members reported using a variety of research and development (R&D) and technical innovation resources. These included internal company R&D groups, R&D sponsored at external academic or contract research organizations, and industry-sponsored research organizations or initiatives.

Notable organizations or programs supported by AF&PA members include:

- **National Council for Air and Stream Improvement (NCASI)** — The forest products industry has pioneered environmental improvement measures since 1943 when the National Council for Air and Stream Improvement (NCASI), a non-profit research institute focused on environmental topics relevant to forest management and the manufacture of forest products, was founded.
- **Institute of Paper Science and Technology (IPST)** — The Institute of Paper Science and Technology (IPST) was created in 1929 to provide science, technology, and education in support of the forest products industry. Today, IPST is an industrial research and development center integrated within the vast resources of the Georgia Institute of Technology. IPST is focused on providing solutions to strategic, economic, scientific, and technical challenges facing the forest products industry.
- **Center for Paper Business and Industry Studies (CPBIS)** — Established in 2000 as part of the Alfred P. Sloan Industry Studies Program and now affiliated with the Industry Studies Association,

the Center for Paper Business and Industry Studies (CPBIS) at the Georgia Institute of Technology is one of 23 Industry Studies Program Centers. The CPBIS mission is to create and disseminate knowledge to further the understanding of business, management, organizational and social issues of importance to the paper industry.

- **Agenda 2020 Technology Alliance** — Agenda 2020 is a non-profit organization established for scientific and educational purposes. Agenda 2020 works to transform the forest products industry through innovation in its manufacturing processes and products. Guided by the 2010 Forest Products Industry Technology Roadmap that presents important R&D needs, Agenda 2020's work addresses the priority R&D needs as determined by member companies. Teams of representatives from member companies, universities, and government work together to form an integrated technology strategy. Agenda 2020 members envision a forest products industry that is fully sustainable, has profitable long-term growth, and continues to reduce its environmental footprint and requirements for energy and water — an industry that is transformed through the use of breakthrough technologies.

Appendix Two:

AF&PA Sustainability-Related Requirements for Members

AF&PA Sustainable Procurement Principles

1. Take part in the Sustainable Forestry Initiative® program as a program participant; or

2. Adhere to the following principles:

i. Support programs that supply regionally appropriate information or services to forest landowners, describing the importance of and providing implementation guidance on best management practices (BMPs); reforestation; afforestation; visual quality management; management of harvest residue; control of invasive exotic plants and animals; characteristics of special sites; and conservation of critical wildlife habitat elements and threatened and endangered species, and Forests with Exceptional Conservation Value.

ii. Encourage landowners to utilize the services of qualified resource professionals and qualified logging professionals in applying principles of sustainable forest management.

iii. Maintain a program for the purchase of raw material from wood producers that have completed training programs and are recognized as qualified logging professionals.

iv. Maintain a program to address adverse weather conditions.

v. Monitor and evaluate the use of BMPs across the wood and fiber supply area.

vi. Monitor the use of BMPs by wood producers supplying the company's facilities and use the information to maintain rates of conformance to best management practices and to identify areas for improved performance.

vii. If the company procures wood fiber outside North America, maintain programs to:

- Promote conservation of biodiversity hotspots and major tropical wilderness areas.
- Ensure fiber sourcing programs support the principles of sustainable forestry, including efforts to thwart illegal logging.
- Assess the risk that fiber-sourcing programs could acquire material from illegal logging.
- Assess the risk that fiber-sourcing programs could take place in countries without effective laws addressing worker safety, fair labor practices, indigenous people's rights, anti-discrimination, anti-harassment, prevailing wages, and worker's right to organize.

viii. Individually and/or through cooperative efforts provide support or funding for forest research to improve forest health, productivity, and sustainable management of forest resources, and the environmental benefits and performance of forest products.

ix. Provide funding and other support for training and education programs to foster improvement in the professionalism of wood producers, including awareness and implementation of sustainable forest management practices.

x. Comply with applicable federal, provincial, state, and local forestry and related environmental and social laws and regulations.

3. Participate in one of the qualifying sustainable forest management programs, including chain-of-custody certification.

AF&PA Environmental, Health & Safety (EHS) Principles

The EHS Principles require members:

- To make environmental, health and safety considerations priorities in operating existing facilities, as well as in the planning of new operations.
- To recognize, in developing and designing products to meet customer needs, the environmental, health and safety effects of product manufacture, distribution, use, and disposal.
- To monitor their environmental, health and safety performance and to report regularly on these matters to their Boards of Directors, as well as to confirm their adherence to these principles annually to the American Forest & Paper Association.
- To train employees in their environmental, health and safety responsibilities and to promote awareness and accountability on these matters.
- To improve environmental, health and safety performance through support of research and development that advances the frontiers of knowledge.
- To communicate with employees, customers, suppliers, the community, public officials, and shareholders to build greater understanding on environmental, health and safety matters.
- To participate constructively in the development of public policies on environmental, health and safety matters.
- To continue to pursue energy conservation, increased energy efficiency, greater utilization of alternatives to fossil fuels, and opportunities for cogeneration of electricity.

AF&PA Sustainability Leadership Highlights

1990
Set first paper recovery goal — 40 percent by 1998

1994
Achieved 40 percent recovery goal

1995
Launched mandatory AF&PA EHS Principles

1996
Set higher recovery goal — 50 percent by 2004

1998
Sustainable Forestry Initiative (SFI®) certification and licensing programs

1999
SFI® Program receives national sustainability award from Renew America and President's Council for Sustainable Development

2000
Published first Environmental, Health & Safety (EHS) Report

2002
Partnered with U.S. State Department to eliminate global illegal logging

2003
Achieved 50 percent goal and set new goal to recover 55 percent by 2012

2005
Launched AF&PA Recycling Awards program

2006
AF&PA member companies reach GHG intensity reduction goal 6 years ahead of schedule

2007
Achieved paper recovery goal early by achieving 56 percent

2008
Set goal to recover 60 percent by 2012

2009
Exceeded 60 percent paper recovery goal ahead of schedule

2011
Launched *Better Practices, Better Planet 2020* sustainability program

Set goal to exceed 70 percent recovery by 2020

2012
Released first sustainability goals progress report

2013
Fifth consecutive year of recovering more than 60 percent of paper in the U.S.

Internet Addresses for Forest Products Organizations

American Forest & Paper Association
www.afandpa.org

National Council for Air and Stream Improvement
www.ncasi.org

Technical Association of the Pulp and Paper Industry
www.tappi.org

Institute of Paper Science and Technology
www.ipst.gatech.edu

Center for Paper Business and Industry Studies
www.cpbis.gatech.edu

Agenda 2020 Technology Alliance
www.agenda 2020.org

Society of Wood Science & Technology
www.swst.org

American Forest & Paper Association®

1101 K Street, NW, Suite 700, Washington, DC 20005
www.afandpa.org

10% total recycled fiber

Comments Received during the Public Review Period on the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014

Commenter: Pamela Lacey

American Gas Association (AGA)

Comment: Meter and Regulator Stations

AGA is pleased that EPA has followed through on its proposal in the Distribution Memo to revise estimated emissions from metering and regulating (M&R) stations by incorporating updated station counts and emission factors from the Lamb et al. study. As we commented before, AGA believes that EPA's proposal to use the updated emission factors and the above grade and below station counts our members report to EPA under 40 C.F.R. Part 98, Subpart W and scaled for national representation results in a more accurate estimate of the actual number of M&R stations.

As we noted in our January comments, we agree that it makes sense to estimate M&R emissions across the time series by using the new updated emission factors for years after 2011 when the Subpart W data became available, to use the 1992-vintage GRI emission factors for early years beginning in 1990, and to use interpolation for the years in between. We agree this is the best approach to more accurately reflect net emissions without the need to subtract Gas STAR program emission reductions.

Comment: Pipeline Leaks

For estimated pipeline leaks in the Draft Inventory, EPA used the previous activity data sources for miles of pipeline by material and for leaks per mile, and the Lamb et al. data on emissions per leak. AGA agrees with this approach, and particularly supports EPA's incorporation of the Lamb et al. pipeline emission factors. As AGA noted in its prior comments, numerous regulatory developments and voluntarily operator actions have resulted in significant reductions in leak rates and incidents, reflected in the overall lower emissions found in the Lamb et al. study. AGA also agrees with EPA's approach to use interpolation between GRI/EPA emission factors in early years and Lamb et al. emission factors in recent years.

Comment: **Residential** Customer Meters

AGA supports EPA's inclusion in the Draft Inventory of revised emission factors for residential customer meters by combining data from the 1996 GRI/EPA study with newer data from a GTI 2009 study and Clearstone 2011 study. As noted in previous comments, the newer data sources, and in particular the GTI 2009 study, include a robust data set composed of numerous data points representing a variety of residencies, including single family homes, duplexes, townhouses, and apartment buildings. Given the homogeneity of the residential meters found at all the distribution companies sampled through the GTI 2009 study, incorporating the new residential meter factor into the GHGI is appropriate.

AGA also supports EPA's update of its customer meter activity data for residential meters to incorporate customer data reported to the U.S. Energy Information Administration (EIA). The customer data is reported to EIA on its Form EIA-176. EIA does not collect data on meters specifically. Rather, EIA instructs respondents to report the average number of consumers served directly from facilities during the year. For residential consumers, this includes master-metered apartments, mobile homes, multi-family dwellings (individually metered), and single-family dwellings. Using data reported to the EIA will improve accuracy compared to the previous GHGI methodology of using 1992 counts driven by gas consumption.

Comment: Commercial & Industrial Meters

AGA is pleased to see that for commercial and industrial meters, EPA has applied the GTI 2009 commercial customer meter emission factor to the total count of commercial and industrial meters in the GHGI. As AGA noted in its prior comments, consistent with EPA's approach in the Draft Inventory, the GTI 2009 industrial meter data should not be incorporated into the GHGI. The GTI 2009 study only took industrial meter measurements from a limited number of sites (46 meters). Due to limited resources, measurements of industrial meters were intended to represent the broad range of meters in this sector, but do not provide a statistical sampling indicative of the industrial meter national inventory, nor does it account for the significant variance in equipment type and size in industrial meters. For this reason, AGA agrees with EPA not to include this data into the GHGI.

AGA also supports EPA's update of its customer meter activity data for commercial and industrial meters to incorporate customer data reported to the EIA. As explained above, the customer data is reported directly to the EIA. Using this data will improve accuracy compared to the previous GHGI methodology of using 1992 counts driven by gas consumption.

Comment: Blowdowns and Mishaps/Dig-Ins

For pipeline blowdowns and mishaps/dig-ins, in the Draft Inventory EPA used PHMSA data of distribution main and service miles for the activity data to calculate the estimate of emissions. Although AGA appreciates EPA's attempt to update the methodology used to calculate emissions from pipeline blowdowns and mishaps/dig-ins, AGA does not believe that EPA's approach provides an accurate representation of the emissions from these sources.

As EPA recognizes, the current approach taken in the GHGI for both sources, which relies on 1992 distribution main and service miles and is scaled by residential gas consumption, results in a mileage estimate that is influenced by factors that would impact natural gas usage, but are unrelated to pipeline miles. AGA agrees with EPA that PHMSA data is a more accurate data source of pipeline miles. Pipeline operators are required to report data directly to the Department of Transportation on an annual basis, which renders the PHMSA data on pipeline mileage an accurate representation of installed pipeline mileage and is superior to the current methodology of estimating pipeline mileage.

However, AGA is concerned with EPA's use of pipeline miles to estimate emissions from blowdowns and mishaps/dig-ins. These sources of emissions are discrete events and there is no available data that suggests a correlation between the number of miles in a pipeline system and the number of mishap events on that system. The number of reported pipeline incidents on gas distribution systems has been flat or down during the past five years; during that time, from 2010 to 2014, the number of miles of installed distribution main in the U.S. has increased by nearly 60,000 miles or 5%.

AGA encourages EPA to use activity data that reflects the reality that an emission blowdown or mishap/dig-in is a discrete event that is not correlated to the number of miles in a pipeline system. AGA recognizes the difficulty in obtaining a comprehensive set of data for these sources of emissions. However, because data associated with both will be reported through EPA's proposed Methane Challenge for companies selecting this best practice, EPA will have more data for possible use in the future to generate activity data for the GHGI. In addition, for mishaps/dig-ins, AGA notes that significant incidents are reported to PHMSA, where significant is defined as an incident above a certain size or impact threshold. [Incidents on natural gas distribution systems are defined as an event that involves a resale of gas from a pipeline that results in a death or significant personal injury, property damage of $50,000 or more, or 3 million cubic feet of lost gas. 49 C.F.R. § 191.3.] AGA recommends consideration of incident data reported to PHMSA and data collected through the Methane Challenge as possible alternative data sources for development of more representative activity data for mishaps/dig-ins.

Comment: New Methodology Obviates Need to Subtract Gas STAR Reductions

In the past, EPA used emission factors based on data collected in 1992 in an EPA-Gas Research Institute (GRI) Study. The agency recognized that practices and materials changed over time, as companies modernized their systems and implemented best practices shared through the Gas STAR program. EPA thus considered the 1992 vintage emission factors to reflect the potential emissions sources could emit in the absence of modernization, and the agency attempted to reflect the effect of continuing modernization by subtracting voluntary reductions reported under the Gas STAR program to calculate net emissions from the sector.

AGA agrees that the new methodology – using new data, including that collected in 2013 from the March 2015 Lamb et al. study and Subpart W reporting – results in a more accurate representation of current operations practices and emissions levels. We agree this obviates the need to continue subtracting voluntary emission reductions achieved through the Gas STAR program to estimate current emission levels for M&R stations, pipeline leaks, and customer meters, since the new data already reflects current practices and emission levels.

Comment: AGA Also Generally Supports the Use of New Data and Methodology for Estimating Methane Emissions from Natural Gas Transmission and Storage

EPA's revisions to the GHGI for the natural gas transmission and storage segment primarily rely upon Zimmerle et al. and an interpolation of existing and new data between the early and current inventory years. Although AGA believes that these approaches can serve as an interim step in EPA's GHGI, AGA encourages EPA to recognize the significantly larger data set available from measurements conducted at transmission and storage compressor stations subject to Subpart W of the GHG Reporting Program. For example, the Subpart W data could be evaluated to assess the relative population of wet seal versus dry seal centrifugal compressors. AGA also believes that Subpart W data can provide a more accurate representation of activity data and device type for pneumatic controllers. AGA encourages EPA to commit to additional updates to the 2017 GHGI report that would integrate Subpart W data.

Commenter: Cynthia A. Finley

National Association of Clean Water Agencies (NACWA)

Comment: NACWA has submitted comments on each of the previous nine Inventories, and we appreciate the clarifications that EPA has made to clarify the emissions calculations and the factors that are used in the calculations. Although the wastewater treatment section has not yet been updated for the 2014 Inventory, EPA states that the same methodology will be used as in the previous Inventory. NACWA previously stated its concern that potentially outdated data was used in the emissions calculations (e.g., the 2004 Clean Watershed Needs Survey). If the same data is used in the 2014 Inventory, our concern remains that the calculations may not accurately reflect current wastewater utility practices. NACWA also believes that more specific emissions factors could be developed for U.S. wastewater treatment.

NACWA understands that EPA will be looking at possible improvements for the wastewater treatment calculations in the next year. NACWA is willing to assist EPA in any way with these improvements, such as providing general information about current wastewater practices or collecting specific data from our member utilities.

Commenter: Evan Weber, William Snape, Lydia Avila, Colette Pichon Battle, Joan Brown, Andres Restrepo, Alan Journet, Erik Schlenker-Goodrich

U.S. Climate Plan, Center for Biological Diversity, Energy Action Coalition, Gulf Coast Center for Law & Policy, New Mexico Interfaith Power and Light, Sierra Club, Southern Oregon Climate Action Now, Western Environmental Law Center

Comment: We respectfully submit these comments on the Draft U.S. Greenhouse Gas Inventory Report: 1990-2014. Our comments are intended to encourage EPA to examine gross U.S. greenhouse gas (GHG) emissions using the most updated values of the Global Warming Potential (GWP) of methane and nitrous oxide. Given recent international news on China's underreporting of its coal consumption and, accordingly, GHG emissions (a November 3, 2015 New York Times article estimates the undercounting at over 900 million metric tons), we believe that the U.S. should place additional importance on accurately quantifying its own GHG emissions.

Our comment states that the Inventory Report, in Annex 6.1, uses an alternative set of GWPs [from the Intergovernmental Panel on Climate Change's 5th Assessment Report (AR5)] that exclude carbon cycle feedbacks, resulting in emissions estimates lower than if EPA were to include these feedbacks. While we understand that EPA excludes these feedbacks to align methodology with the GWPs used in the main text of the Inventory Report, we believe that these higher emissions estimates, which represent the full climate impact of methane and nitrous oxide, must be presented to the public.

It is our goal to increase the transparency by which the EPA reports U.S. GHG emissions to the global community. We believe that using GWPs inclusive of carbon cycle feedbacks accomplishes this goal.

Comment: In Section 6.1 of the U.S. GHG Inventory, Table A-282 presents alternative scenarios of greenhouse gas emissions estimates if EPA used GWPs from the IPCC Fifth Assessment Report (AR5), rather than the Fourth Assessment Report (AR4). However, this analysis underestimates the GWP of CH_4

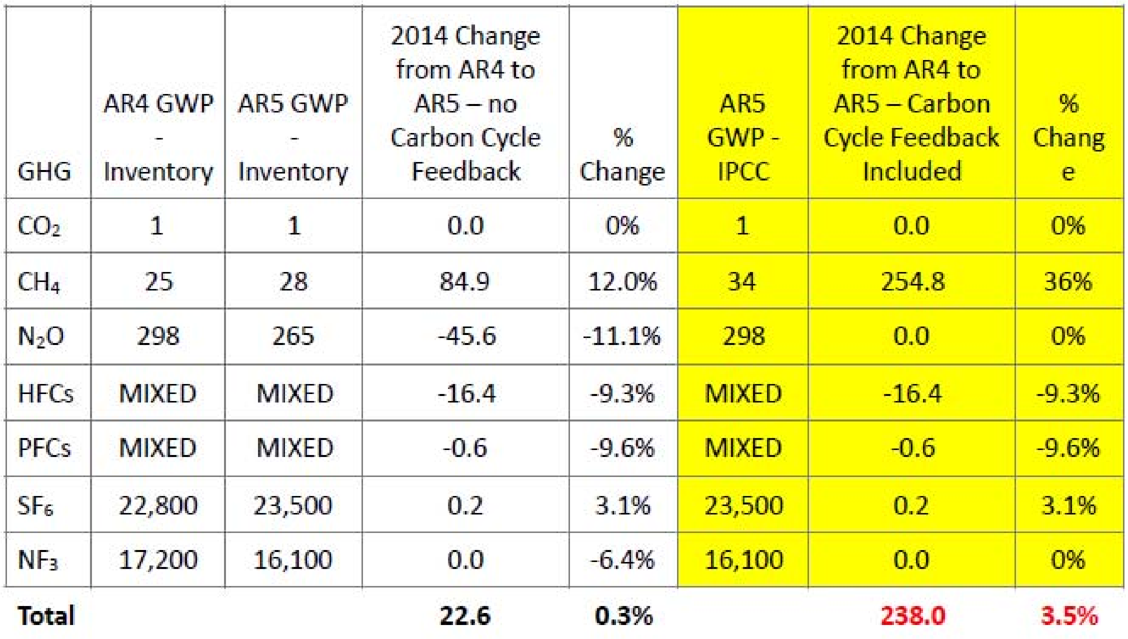
and N_2O, based on Table 8.7 (page 714) of the AR5 Working Group I report. This underestimation results from excluding "carbon cycle feedbacks" previously not quantified in AR4. Table 1 shows that by including these feedbacks for AR5 100-year GWPs, the emissions increase (relative to AR4 values) is far higher than EPA presents. While EPA reports this increase to be 22.6 (0.3% higher than AR4 total emissions) $MMTCO_2e$, the true value is 238.0 (3.5% higher) $MMTCO_2e$. According to WRI's CAIT tool, this additional 215.4 $MMTCO_2e$ is roughly equal the gross emissions of Norway, Sweden, Denmark, and Finland—combined.

Our analysis does not include the following factors, which we believe indicate that our upward adjustments are actually conservative:

- IPCC indicates that the GWP of biogenic methane is 34, whereas fossil methane is 36, over a 100-year time horizon. Given that over one-third of U.S. methane emissions are fossil (from natural gas systems, coal mining, and petroleum systems), the change in methane from AR4 to AR5 should be greater than our value of 254.8.
- EPA's also underestimates the GWP of HFC-134a, which represents 40% of Emissions from Substitution of Ozone Depleting Substances – the AR5 value EPA uses is 1,300, whereas IPCC, including carbon cycle feedback, uses 1,550. Other high-GWP gases, whose carbon cycle feedbacks are not quantified in Table 8.7, very likely have higher GWPs than EPA uses in Annex 6.1, though the lack of IPCC data prevents us from quantifying this.

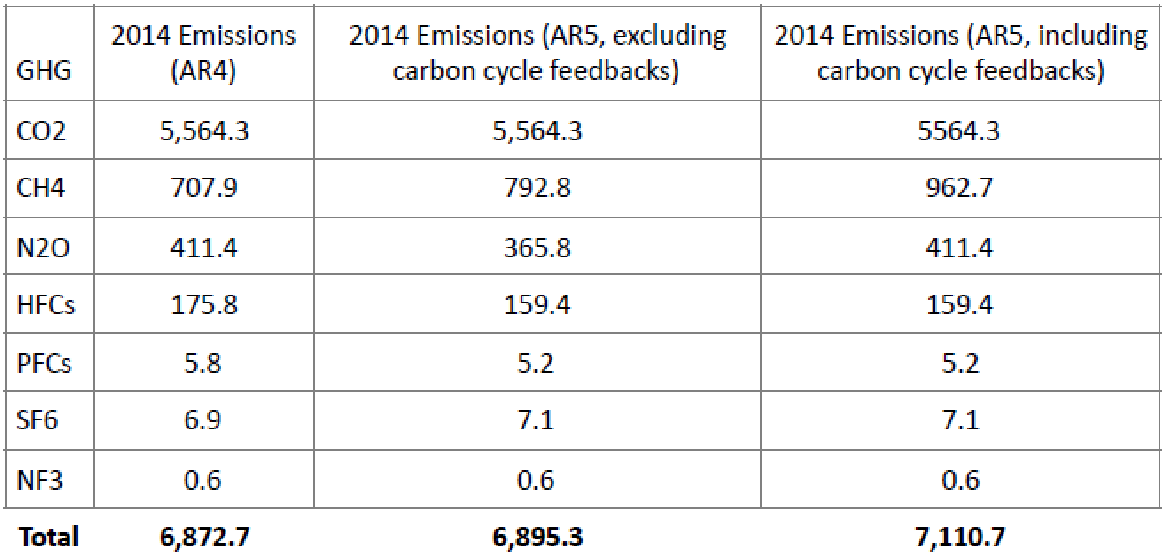
These emissions must be presented to the public. We do understand that EPA has chosen not to include the carbon cycle feedbacks from CH_4 and N_2O for the AR5 GWPs in order to align methodologies with AR4. However, given that the GWPs highlighted yellow in Table 1 below are the "true" values, we see no reason to keep the lower AR5 numbers, as changes in methodology to quantify carbon cycle feedbacks are precisely the goal of updated scientific research. If consistency between methodologies really is necessary (though again, this shouldn't be a reason not to use the higher values), then we recommend communicating these findings in addition to the previous ones. Table 2 presents the GHG emissions totals by gas, for further transparency as to how we calculated the differences between emissions for each GWP accounting method.

Table 1 - Changes in Emissions using AR4 GWPs, AR5 GWPs Excluding Climate Feedbacks, and AR5 GWPs Including Climate Feedbacks



GHG	AR4 GWP - Inventory	AR5 GWP - Inventory	2014 Change from AR4 to AR5 – no Carbon Cycle Feedback	% Change	AR5 GWP - IPCC	2014 Change from AR4 to AR5 – Carbon Cycle Feedback Included	% Change
CO_2	1	1	0.0	0%	1	0.0	0%
CH_4	25	28	84.9	12.0%	34	254.8	36%
N_2O	298	265	-45.6	-11.1%	298	0.0	0%
HFCs	MIXED	MIXED	-16.4	-9.3%	MIXED	-16.4	-9.3%
PFCs	MIXED	MIXED	-0.6	-9.6%	MIXED	-0.6	-9.6%
SF_6	22,800	23,500	0.2	3.1%	23,500	0.2	3.1%
NF_3	17,200	16,100	0.0	-6.4%	16,100	0.0	0%
Total			**22.6**	**0.3%**		**238.0**	**3.5%**

Table 2 - GHG Emissions Totals by Gas using IPCC's AR4, EPA's AR5, and IPCC's AR5 GWPs



GHG	2014 Emissions (AR4)	2014 Emissions (AR5, excluding carbon cycle feedbacks)	2014 Emissions (AR5, including carbon cycle feedbacks)
CO2	5,564.3	5,564.3	5564.3
CH4	707.9	792.8	962.7
N2O	411.4	365.8	411.4
HFCs	175.8	159.4	159.4
PFCs	5.8	5.2	5.2
SF6	6.9	7.1	7.1
NF3	0.6	0.6	0.6
Total	**6,872.7**	**6,895.3**	**7,110.7**

Commenter: Brad Upton
National Council for Air and Stream Improvement, Inc. (NCASI)

Comment: The estimated forest ecosystem carbon stock changes reported in the draft 1990-2014 national inventory are significantly different than those reported previously. The text in the report explains that this is due, at least in part, to new estimation methods (described in Woodall et al. 2015) and reclassification of land in Alaska. It is our understanding that the new estimates rely more heavily on measured data (compared to model-generated data) than earlier estimates and, as a result, are likely to be more accurate. It would be helpful for the text in the report to elaborate on the benefits of greater reliance on measured vs. modeled data in the updated estimates.

Comment: While the report contains a summary of the recalculations of forest ecosystem carbon, it is unfortunate that the annexes have not been updated to provide a full explanation of the sources of the difference between the new and previous estimates. We encourage the agency, in future years, to make the annexes available for comment at the same time the report is made available.

Comment: Changes in carbon stocks in products-in-use are also significantly different than in previous inventories, but this is not acknowledged or explained in the report or the annexes. This should be discussed in the report and examined in more detail in the annexes.

Comment: In Chapter 7 Waste on page 7-11, line 1, EPA states that the degradable organic carbon (DOC) value for landfilled pulp and paper waste was revised from 0.20 to 0.15 based on a literature review and data reported under 40 CFR Part 98 (referred to as the Greenhouse Gas Reporting Program, GHGRP, the new DOC value is also discussed in Chapter 9 Recalculations and Improvements on page 9-1, line 39, and in Annex 3.14 on page A-391, line 38). The new value of 0.15 corresponds to a weighted average of all DOC values reported to the GHGRP within subpart TT by pulp and paper facilities in 2013. It is stated in a reference supporting the draft inventory (RTI 20152) that 72% of the pulp and paper facilities that reported to subpart TT used only the default DOC values from Table TT-1 and that 49% of the reported waste quantities were associated with the default DOC value for general pulp and paper industry waste other than industrial sludge (0.20). Therefore, the new DOC value used in the draft inventory (0.15) is heavily influence by use of the default value of 0.20 in Table TT-1.

The current default DOC for general pulp and paper industry waste other than industrial sludge in Table TT-1 (0.20) is based on an erroneous interpretation of IPCC guidance, as documented by NCASI in prior communications with EPA (NCASI 20113). Therefore, it is inappropriate to include data elements corresponding to the default value of 0.20 when developing a new DOC value for use in the inventory. As noted in RTI 2015, 28% of pulp and paper facilities that reported to subpart TT developed DOC values specific to their landfilled waste streams by analysis using methodologies specified by EPA. It is more technically appropriate (and accurate) to develop a DOC value for pulp and paper industry waste from a weighted average of these waste stream-specific DOC values reported to the GHGRP, as these values represent the characteristics of the actual waste placed in industrial landfills at pulp and paper mills and would not be influenced by the erroneous general DOC value of 0.2. RTI 2015 presents such a weighted average DOC value for pulp and paper industry wastes, which is 0.10. EPA should use a DOC value of 0.10 rather than 0.15 in developing estimates of methane emissions from industrial landfills at pulp and paper mills.

Comment: In Annex 3.14 on page A-391, line 38, EPA incorrectly associates the new DOC value for pulp and paper industry waste (0.15) with an L_0 value of 49 m^3/MT. An L_0 value of 49 m^3/MT correlates with a DOC value of 0.10, which is the technically appropriate DOC value to use in the agency's top down analysis as explained above. On line 47 the agency states that "data were available through the GHGRP to warrant a change to the L_0 (DOC) from 99 to 49 m^3/MT…" Note that the previous DOC (0.20) is correlated with an L_0 of 99 m^3/MT, and further note that DOC is directly proportional to L_0. Therefore, halving L_0 (from 99 to 49 m^3/MT) would result in DOC also being halved (i.e., from 0.20 to 0.10).

Comment: As conveyed in our comments on the public review Draft US Inventory of Greenhouse Gas Emissions and Sinks: 1990-2013 (included herein as Appendix A), production statistics developed by EPA for use in waste-related GHG emissions calculations for the pulp and paper sector are too high. Table 7-12 lists 2013 production of the pulp and paper sector at 131.5 million metric tons, based on data from the Food and Agriculture Organization of the United Nations (FAO), and includes a note that this figure represents the sum of woodpulp production plus paper and paperboard production. The same production figures are presented in RTI 2006, which describes EPA's method for estimating industrial landfill emissions. Summing woodpulp, paper, and paperboard production results in double counting, because the majority of woodpulp production is used to produce paper and paperboard at integrated mills (an integrated mill includes both pulping and papermaking at the same facility).

A more appropriate method for characterizing total pulp and paper sector production would be to sum paper production, paperboard production, and market pulp production [Market pulp is produced at a pulp mill and then sold rather than being used at the same mill to produce paper or board]. For 2013, the American Forest and Paper Association reported total production of paper and paperboard to be approximately 73 million metric tons and total production of market woodpulp to be approximately 8 million metric tons (AF&PA 2014). Based on these statistics, total pulp and paper sector production in 2013 was approximately 81 million metric tons.

EPA's method of using the FAO statistics overstates the pulp and paper industrial sector's production, which in turn results in estimates of pulp and paper sector industrial wastewater treatment and landfill methane emissions being far too high. On page 7-28 of the Draft US Inventory of Greenhouse Gas Emissions and Sinks: 1990-2014, lines 42-47, EPA notes that the agency is evaluating new approaches to estimating industry-level production (and other values) used in estimating industrial wastewater treatment GHG emissions. The agency should use production data from AF&PA's Statistical Summary reports in calculating both wastewater treatment and landfill emissions from the pulp and paper sector, which will result in more accurate characterization of industrial waste-related methane emissions from this sector.

Commenter: Michael Schon

Portland Cement Association (PCA)

Comment: The Draft Inventory's approach to accounting for emissions associated with cement production does not consider available data, however, or determine whether those data are consistent with the conclusions reached by the Draft Inventory. In addition, the Draft Inventory does not present a comprehensive and easily discernible estimate of the industry's total GHG emissions. This issue makes verification of the total emissions associated with cement production impossible and also masks efficiency improvements by the sector. In these comments, PCA suggests areas for improvement to address these concerns.

Comment: As the Draft Inventory acknowledges, GHG emissions are released at two points in the production of cement—an essential component of concrete. First, the combustion of fuel to heat cement kilns and to enable necessary chemical reactions produces GHG emissions. Thanks to efficiency improvements, including use of carbon-neutral alternative fuels, cement production plants reduced combustion-related emissions per unit of production in recent years. Second, emissions are generated through calcination, a chemical reaction that produces calcium oxide—a foundational component of cement. Calcium carbonate is converted to calcium oxide and carbon dioxide: $CaCO_3 \rightarrow CaO + CO_2$. There is little opportunity to reduce the calcination process- related CO_2 emissions per unit of production.

Comment: EPA developed a Greenhouse Gas Reporting Program (GHGRP) for cement plants to inventory both of these types of emissions on a facility-specific basis. Under Subpart H to 40 C.F.R. Part 98, all cement production plants in the United States must report both their combustion-related and process-related emissions. 40 C.F.R. §§ 98.80, 98.82. EPA now has five years of reported data from those facilities on file. In 2010, an Intergovernmental Panel on Climate Change (IPCC) task force encouraged the consideration of GHGRP data in the development of the annual inventory of domestic GHG emissions that EPA submits to the United Nations in accordance with the United Nations Framework Convention on Climate Change (UNFCCC).

Yet this year's draft domestic inventory, like its predecessors, still does not consider the GHGRP data for cement production, including whether those data points are in line with the GHG estimations presented in the Draft Inventory. Rather, EPA punts on considering those data. This is a missed opportunity to evaluate facility-specific data, as EPA itself acknowledges.

Comment: In the Draft Inventory, EPA also misses an opportunity to analyze emissions associated with cement production in a comprehensive manner. While the process-related emissions of cement production are addressed in the Industrial Processes and Product Use chapter of the Draft Inventory, the combustion-related emissions of cement production are not disaggregated from other industries' combustion-related emissions in the Energy chapter. The Draft Inventory estimates total process-related cement production emissions at 38.8 MMT CO_2e in 2014, but presents no equivalent figure for the combustion-related cement production emissions. This makes it impossible to determine the total emissions generated by the industry.

Thus, PCA cannot comment on whether the Draft Inventory's accounting of cement production emissions is defensible or accurate. We encourage EPA to calculate and present an overall emissions figure associated with cement production so that it can be compared to the total reported cement production emissions of 67.6 MMT CO_2e in 2014 under the GHGRP.

Comment: PCA also encourages EPA to consider cement production emissions not only on a total mass basis but also on a production rate basis so that efficiency improvements are apparent. As economic conditions have improved, demand for cement has increased, resulting in an increase in the total tons of emissions. Importantly, however, significant efficiency improvements, on an emissions per unit of production basis, have also occurred.

Commenter: Kerry Kelly

Waste Management (WM)

Comment: We have gained considerable experience by implementing the Mandatory GHG Reporting Rule (GHG MRR) since 2010, reporting emissions for active and closed Municipal Solid Waste (MSW) landfills and associated renewable energy projects. The landfill sector has significant interest in the Draft Inventory since EPA, for the first time has used annual waste disposal data reported by MSW landfills under Subpart HH of the GHG MRR, in its Draft Inventory emissions estimates. We very much want to work with you to ensure that GHG MRR data are used correctly to refine the Draft Inventory for MSW landfill emissions.

We commend EPA for using GHG MRR data to refine the inventory estimates of emissions. As EPA states in Chapter 7 –Waste, of the Draft Inventory (at 7-7), the EPA rigorously verifies data provided by reporters subject to the GHG MRR. Moreover, reporters certify the data as true and accurate before submitting it to the Agency, and must collect data and ensure its quality in accordance with GHG MRR requirements and the facility's GHG Monitoring Plan. Thus, data developed for the GHG Reporting Program (GHGRP) is of known quality and has far greater certainty than other databases EPA has relied upon. Using reporting data and emissions calculations prepared for the GHGRP should enhance the quality and validity of the nationwide inventory.

Comment: Because of the emphasis on accuracy and verification with GHG MRR data, we were surprised with the changes to MSW landfill emissions estimates in the Draft Inventory. We believe that thorough evaluation of the databases must be undertaken before EPA can confidently express 2015 emissions using the GHG MRR data. The changes in net emissions, and amounts of methane flared and used for energy appearing in the draft inventory are very significant and negative. The 24-year methane reduction performance achieved by MSW landfills working to comply with EPA control standards dropped from a projection of 38% reduction to a mere 1.4% reduction. We could not replicate the Agency's calculations, and they appear to be in contravention with other data all agree to be reliable.

Specifically, there appears to be a fundamental disconnect between the estimated emissions reported by MSW landfills subject to the GHGRP and the estimated emissions reported in the Draft Inventory. The GHGRP emissions from MSW Landfills in 2014 were 91.5 MMT CO_2e. EPA designed the GHGRP to obtain the highest possible percentage of emissions from each reporting sector, while minimizing the total number of facilities that would be required to report. EPA selected a reporting threshold for MSW landfills based on estimated methane generation of 25,000 MT CO_2e or greater, and estimated that the MSW landfills reporting under GHGRP comprise 82% of total national emissions of MSW landfills for both active and closed landfills.

The inconsistency in the emissions reported becomes evident when comparing the 2014 emissions from the GHGRP to those estimated in the Draft Inventory for the same year. If 91.5 MMT represents 82% of MSW landfill emissions, then logically, the total from all MSW landfills will be approximately 111.5 MMT CO_2e. Instead, total emissions from MSW landfills are 167 MMT CO_2e, and emissions for the landfill sector (both MSW and industrial landfills) are 181.8 MMT CO_2e.

Comment: The landfill sector representatives appreciated your meeting with us to describe the process used to integrate GHGRP annual waste disposal figures into the Draft Inventory. Since we first reviewed these estimates, we have been attempting to discover what factors led to a total methane generation of almost twice as much as what was in the GHGRP data. This is a challenging exercise because the database has been structured in such a way to make accessing all of the relevant information very difficult.

Comment: We found a significant source of error in the use of GHGRP annual waste disposal figures in the Draft Inventory because the waste was not properly differentiated between degradable waste and inert materials. Since only degradable waste produces methane, applying the degradation factor (or DOC) for bulk MSW to all waste disposed (even separate inert waste streams that do not degrade) significantly over predicts methane generation.

We looked first at the public database for the GHGRP (Envirofacts) to assess how many reporters in 2014 characterized their annual waste receipts to identify inert materials. Because Envirofacts does not capture the waste type descriptor provided by reporters, one must query the database to identify reporters using various DOC values for different waste streams and sum those fractions to one. For 2014, 944 landfill sites reported accepting waste. Of those 944 reporting annual waste receipts, 42% reported receiving inert waste, using the waste composition option to delineate inert wastes (DOC=0), and combining separate C&D waste streams with MSW under the bulk waste category, or by using the modified bulk waste option showing (MSW DOC=0.31 C&D DOC=0.08, Inert DOC=0).

In fact, because it is so difficult to identify reported waste types in Envirofacts, we turned to the SCS Engineers database, which contains all required reporting elements from 2010-2014 for 544 MSW landfill GHGRP reporters, or 44% of the total number of reporters, and 50% of the annual waste receipts. The landfills in this database include both private and municipal sites located across the country. Looking at GHGRP annual disposal amounts for the 544 sites in 2014, 23% of waste disposed was reported as inert. The prior reporting years 2010-2013, had similar percentages of waste reported as inert (ranging from 17% in 2010 to 22.5% in 2013), with the amount of inert waste growing in each year. This is consistent with the current emphasis on diversion of organic wastes from landfills, and efforts by landfills to make up the difference with inert waste streams such as ash and soils.

We also evaluated the GHGRP waste disposal history for these 544 sites (including total waste in place -- WIP). Of the total WIP, 8.1% is inert. However, WIP data is far less definitive than annual waste disposal information because most reporters did not have historical data, or chose to estimate historical waste in place as MSW and did not characterize the different waste streams (MSW, C&D, inert) disposed in the landfill.

Waste Management did report well-characterized waste back to 1999 for most sites. A review of this information showed that from 1999 through 2015, there has been a 21.5% drop in the amount of MSW waste disposed in landfills, a 21% increase in inert wastes, and an 11% increase in C&D waste. These findings comport with the experience of public and private landfills across the country. Increased recycling and organics diversion initiatives have resulted in a decline in MSW landfill disposal, yet for many landfills receipt of inert waste streams has steadily increased.

Based on our analysis of the three datasets, we believe the annual waste disposal volumes used in the Draft Inventory to calculate methane generation were likely assigned inappropriately high DOC values, resulting in an over prediction of methane generation. This in turn led to inflated estimates of methane emissions from MSW landfills.

Comment: We know that you share our interest in assuring the final Inventory is as accurate as possible. The information in the Draft Inventory presents major, adverse policy implications for the Administration and EPA. The current draft could be interpreted to contradict White House and Agency regulatory statements, plans and documents with regard to methane controls, vitiate the effectiveness of the EPA's twenty-year old New Source Performance Standards (NSPS) and Emission Guidelines (EG) Rules, and undermine the accomplishments of the Landfill Methane Outreach Program (LMOP). These very serious impacts must certainly be avoided if they result from a misinterpretation of GHGRP waste disposal data because the inventory database simply does not fully characterize waste types and their potential to generate methane over time.

The landfill sector wants to work with you to ensure that the GHGRP data are appropriately used, and the resulting estimated emissions are representative of MSW landfill disposal and gas collection and control practices. We are concerned that there is limited time for the Agency to conduct a thorough reevaluation of the data and make the necessary changes. If the Agency were to publish the Draft Inventory results as they appear in the current draft, public officials and community residents would be misinformed about landfill emissions, and there could be significant policy and economic repercussions for the sector.

To allow sufficient time for correction of the draft estimate, in the short-term, we urge EPA to use the 2015 Inventory data and protocols for estimating MSW landfill emissions. For future inventories, we encourage the Agency to make use of the emissions calculations developed and certified by GHGRP reporters under the force of law. The Agency has been proactive in improving the estimation of landfill methane emissions by updating GHGRP protocols. Use of these verified emissions data could only enhance the U.S. Inventory, while reducing administrative burdens on Agency staff. We urge EPA to work with the landfill sector to develop a methodology to incorporate GHGRP results and the growing body of measured methane emissions into the nationwide inventory – much as you are doing with the natural gas sector. We believe this is a wise practice, and we commit to do everything possible to assist your review.

Commenter: Luis Orlindo Tedeschi

Texas A&M University

Comment: I know this is past the date of March 23, 2016, but I really wanted to make sure this is addressed. I noticed in Table 5-3, the order of Horses, Sheep, and Swine might be incorrect. Looking at previous reports, you had Swine, Horses, and Sheep, and the numbers for the current inventory don't match my expectations. I'd think that Swine is greater than horses and sheep, and sheep is greater than horses.

DRAFT, 1990-2014 Inventory Report:

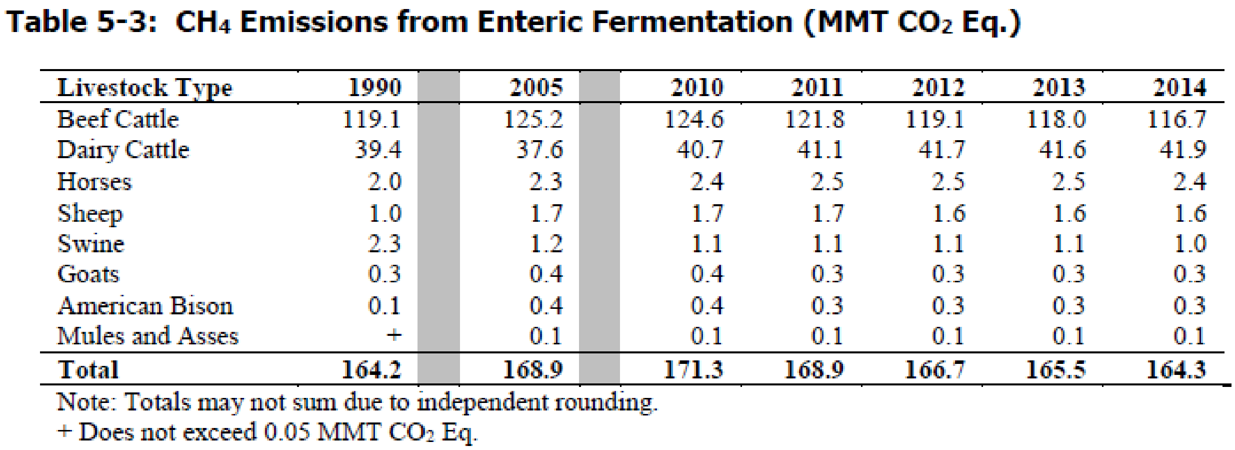


Table 5-3: CH$_4$ Emissions from Enteric Fermentation (MMT CO$_2$ Eq.)

Livestock Type	1990		2005		2010	2011	2012	2013	2014
Beef Cattle	119.1		125.2		124.6	121.8	119.1	118.0	116.7
Dairy Cattle	39.4		37.6		40.7	41.1	41.7	41.6	41.9
Horses	2.0		2.3		2.4	2.5	2.5	2.5	2.4
Sheep	1.0		1.7		1.7	1.7	1.6	1.6	1.6
Swine	2.3		1.2		1.1	1.1	1.1	1.1	1.0
Goats	0.3		0.4		0.4	0.3	0.3	0.3	0.3
American Bison	0.1		0.4		0.4	0.3	0.3	0.3	0.3
Mules and Asses	+		0.1		0.1	0.1	0.1	0.1	0.1
Total	**164.2**		**168.9**		**171.3**	**168.9**	**166.7**	**165.5**	**164.3**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO$_2$ Eq.

1990-2012 Inventory Report:

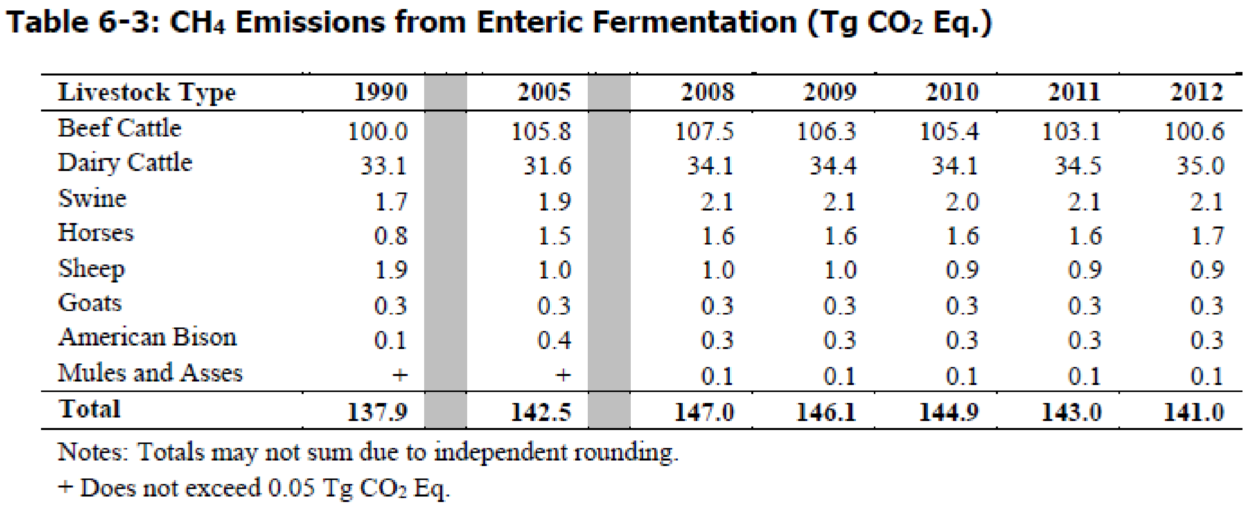


Table 6-3: CH$_4$ Emissions from Enteric Fermentation (Tg CO$_2$ Eq.)

Livestock Type	1990		2005		2008	2009	2010	2011	2012
Beef Cattle	100.0		105.8		107.5	106.3	105.4	103.1	100.6
Dairy Cattle	33.1		31.6		34.1	34.4	34.1	34.5	35.0
Swine	1.7		1.9		2.1	2.1	2.0	2.1	2.1
Horses	0.8		1.5		1.6	1.6	1.6	1.6	1.7
Sheep	1.9		1.0		1.0	1.0	0.9	0.9	0.9
Goats	0.3		0.3		0.3	0.3	0.3	0.3	0.3
American Bison	0.1		0.4		0.3	0.3	0.3	0.3	0.3
Mules and Asses	+		+		0.1	0.1	0.1	0.1	0.1
Total	**137.9**		**142.5**		**147.0**	**146.1**	**144.9**	**143.0**	**141.0**

Notes: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 Tg CO$_2$ Eq.

Commenter: Jean Bogner

University of Illinois - Chicago

Comment: The purpose of this letter is to, first, document the deficiencies of the current IPCC (2006) FOD model for landfill methane generation, recovery, and emissions as currently applied to U.S. sites under the GHGRP HH- methodologies [Spokas et al., 2011, 2015; Bogner et al., 2010, 2014, 2016]. In general, IPCC (2006) relies on 40-year old science using a 1970's landfill gas generation model as well as a default 10% oxidation value based on a 20-year old study for oxidation at one U.S. site (Czepiel et al., 1996a,b). Importantly, neither IPCC (2006) nor the recent modifications for oxidation and emissions added to the GHGRP methodologies explicitly model the major climate drivers for emissions now known from literature.

Comment: In addition, these model applications lack comprehensive field-validation for emissions. See Appendix A for more detailed discussion.

Comment: A second purpose is to introduce an existing, freely-available [www.ars.usda.gov], fully-documented, user-friendly JAVA tool for landfill methane emissions inventory reporting. This model [CALMIM] was developed using established relationships for gaseous & heat transport, then independently field-validated.

Comment: Instead of relying on a landfill gas generation model, CALMIM explicitly models landfill methane emissions based on 1-dimensional gaseous, heat, and water transport in each cover material for a typical annual cycle of 365 days. The major drivers are: 1) the individual cover thicknesses and physical properties at a specific site; 2) the annual climate cycle for each cover as it affects soil moisture and temperature at various depths and, in turn, methane transport and oxidation rates; and 3) the physical effect of engineered gas recovery on soil gas concentration gradients.

Comment: A third purpose is to initiate discussion regarding the application of CALMIM as an alternative to IPCC (2006) for landfill methane emissions inventory reporting under the GHGRP. As stated in IPCC (2006), "higher order validated" models are permitted under IPCC national GHG inventory guidelines.

Comment: In general, very wide ranges for methane emissions and oxidation had been quantified, often not aligning with the 10% value and ranging from negligible to >100% (uptake of atmospheric methane).

Comment: It is reasonable to point out that, in the intervening years, the expected temporal variability of oxidation rates over an annual cycle in site-specific cover materials has often been overlooked. In short, oxidation is a variable, not a constant, for each specific cover material at a specific global location.

Comment: Regarding b), potential improvements to the underlying IPCC (2006) FOD gas generation model, there were many problems with trying to fit this conceptual model to a growing database of site-specific field measurements for emissions. Those problems included large mismatches between modeled & measured emissions, a primary dependency for FOD-modeled methane emissions on waste in place for the California inventory [Appendix A] irregardless of waste composition data & k values, and observational data from current California sites where measured gas recovery rates were robustly & linearly related to WIP only [Appendix A; Spokas et al., 2015]. Thus CALMIM was developed as a new "emissions-only" model as discussed in Appendix B.

Commenter: Karin Ritter

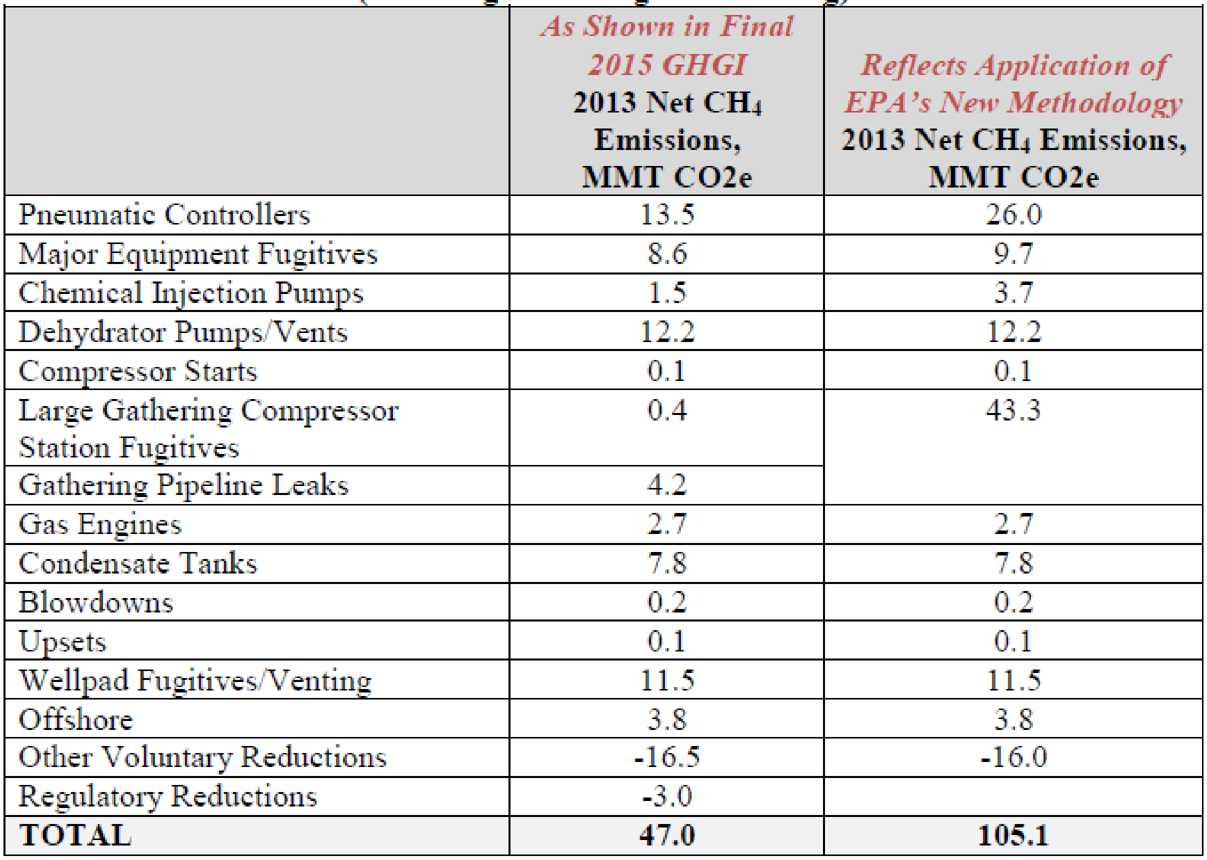
American Petroleum Institute (API)

Comment: In lieu of a formal expert review process of the Preliminary Draft of the national GHG Inventory (GHGI), as was customarily done in past years, EPA released several memos between December 2015 and February 20161 outlining revisions under considerations for estimating GHG emissions from the Distribution, Transmission & Storage, Gathering & Boosting and Petroleum & Natural Gas production segments of the Petroleum and Natural Gas Systems sector. API's comments on those memos are provided herein as an attachment starting on page 6.

Comment: While the last set of memos on Production and Gathering and Boosting were still under expert review, EPA released the Public Review Draft of the GHGI, already incorporating the revisions that were dubbed “under consideration” in EPA’s memos, without providing industry the opportunity to comment on these proposed revisions, or for EPA to incorporate industry’s expert comments, prior to releasing the Draft GHGI for public review. In addition, the released Public Review Draft does not provide specifics on the revised methodological changes for specific sources and lacks the normal methodological details usually provided in the applicable Annexes.

Comment: Based on information provided in the memo Inventory of U.S. Greenhouse Gas Emissions and Sinks: Revisions under Consideration for Natural Gas and Petroleum Production Emissions (February 2016, Table 4), API attempted to recreate the production sector emission data reported in Table 3-43 of EPA’s Public Review Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks. The following table summarizes API’s comparison of 2013 source level emissions published in the April 2015 GHGI and the 2013 emission estimates from Table 3-43 of the recent Public Review version of the GHGI.

Table 1. Comparison of 2013 Emission Estimates for Natural Gas Production (including Gathering and Boosting)



	As Shown in Final 2015 GHGI **2013 Net CH_4 Emissions, MMT CO2e**	*Reflects Application of EPA’s New Methodology* **2013 Net CH_4 Emissions, MMT CO2e**
Pneumatic Controllers	13.5	26.0
Major Equipment Fugitives	8.6	9.7
Chemical Injection Pumps	1.5	3.7
Dehydrator Pumps/Vents	12.2	12.2
Compressor Starts	0.1	0.1
Large Gathering Compressor Station Fugitives	0.4	43.3
Gathering Pipeline Leaks	4.2	
Gas Engines	2.7	2.7
Condensate Tanks	7.8	7.8
Blowdowns	0.2	0.2
Upsets	0.1	0.1
Wellpad Fugitives/Venting	11.5	11.5
Offshore	3.8	3.8
Other Voluntary Reductions	-16.5	-16.0
Regulatory Reductions	-3.0	
TOTAL	**47.0**	**105.1**

As is shown in the table above, total emissions for Natural Gas Production operations are estimated to increase from 47 million metric tonnes (MMT) CO2e as published in last year’s GHGI, to 105 MMT

CO_2e, which indicates more than a doubling of emissions. It appears that EPA intends to include approximately 16 MMT CO_2e in emission reductions from voluntary activities, although it is unclear to which sources these emission reductions will apply. It is also unclear if fugitive emissions from wells are included under "Wellpad Fugitive Venting" or under "Major Equipment Venting". API is concerned that these additional details are not available for review and comment ahead of the final GHGI that is scheduled to be published in April 2016.

Comment: For Petroleum and Natural Gas Systems, EPA provides "computed" emission values for calendar year 2013, using the proposed, revised methodologies from EPA's sector specific memos. Emissions for the years 1990-2012 are not back-cast or updated, and EPA does state in the Public Review draft that the 2013 emissions estimates are preliminary and subject to revision in the final GHGI. As a result, it looks like a large step-change in estimated emissions for 2013 resulting from EPA's methodological changes. The new methodology used by EPA, especially for the Petroleum and Natural Gas production segments of the industry, does not reflect a "real" increase in emissions but rather improved availability of some industry activity data as reported to the GHGRP. The improved industry activity information provided by larger facilities, which are above the GHGRP reporting threshold, is being used by EPA for scaling up to the nationwide inventory without recognizing that the smaller (non-reporting) facilities likely have very different activity characteristics and thus should not be included in the scaled up activity factors proposed by EPA.

Comment: The estimated Petroleum Systems emissions for 2013 indicate a 151% increase as compared to what was previously reported for 2013 and is driven by an assumed increase of 157% in Petroleum Production emissions. This assumed emissions increase from Petroleum Production is due to EPA's scaling up the count of pneumatic controllers and process fugitive components as reported through the GHGRP. This does not reflect the fact that smaller production sites, which are not subject to GHGRP reporting, have much smaller component counts per wellhead and many of them use little – if any – pneumatic controllers, particularly in petroleum systems . Most importantly, EPA did not revise the emission factors used for characterizing overall emissions from pneumatic controllers and fugitive sources, despite repeated comments from industry that these factors are outdated and overestimate emissions from properly functioning pneumatic controllers and typical process components.

Comment: For Natural Gas Systems, EPA estimates that 2013 emissions would increase 23% after applying EPA's new estimation methodology. The data for individual segments such as production, processing, transmission & storage and distribution show a respective emissions change of 136%, 0%, -47% and -64%. Again, the change of 136% in the production segment is due to extrapolation of pneumatic controllers and process fugitive component counts from the GHGRP to a nationwide basis, as well as using the same overestimation of component counts for smaller production sites that do not report to the GHGRP. The change in Natural Gas Production also includes a new and very large estimate for Gathering and Boosting compressor stations based on limited, short-duration, downwind measurements. API does not believe the data used to derive emissions for Gathering and Boosting stations are sufficient for determining national emissions from these operations due to the large uncertainty associated with the measurement method on which they are based.

Comment: For some activity data, larger equipment counts would be expected for the types of sites that are more likely to be reported in the GHGRP. However, applying data from GHGRP sites to the entire population of U.S. wells is inappropriate. For example, emergency shut-down devices (ESDs) may be counted as pneumatic controllers in the GHGRP but have very different emission characteristics (infrequently emitting) than the types of pneumatic controllers that are assumed in the GHGI.

Comment: EPA's approach appears inconsistent. First, EPA notes that Subpart W GHGRP data covers 32% of the active wellheads for 2013 and proposes to use this percentage to "scale" some emission sources to a national level. Simultaneously EPA states that the GHGRP Subpart W data covers the majority of national oil and natural gas production sources. Separately, EPA has also determined that Subpart W covers about 85% of the GHG emissions from the onshore oil and natural gas production sector as indicated in the Subpart W Technical Support Document.

Comment: Clearly, if Subpart W covers 85% of the GHG emissions from theoil and natural gas production sector, then there is no basis for changing the GHGI in a manner that estimates 90% higher overall GHG emissions (based on the recalculated 2013 inventory). This discrepancy of GHGRP Subpart W emissions coverage must be fully explored and explained prior to making the proposed changes to derive GHG emissions for this sector in the GHGI. Given that the GHGRP Subpart W reported GHG emissions are substantially less than in the estimated GHGI emissions for 2013, the resultant scaling of the GHGRP data to national GHG emissions should be less than the 15% of emissions EPA previously determined are not covered by GHGRP Subpart W.

Comment: API agrees that updated GHGI activity factors and emissions data are warranted and as such recommends that EPA form a multi-stakeholder working group comprised of industry, governmental, and environmental organizations active in GHG emissions measurements and estimation to evaluate recently published data that may be considered for updating the national GHGI prior to rushing to implement the proposed revisions that are based on invalid extrapolation of GHGRP data from large facilities to non-reporting smaller installations.

Comment: API recognizes that emerging data from recent field studies have raised concerns about measurements uncertainty, and recognizes the need for a thorough discussion of means of improving the methodology to ensure collection of robust measurement data. API proposes that a working group – as discussed above - be convened following the completion of the 2014 GHGI (April 2016) to provide a structured framework for consultation and review of GHGI updates. An early start (April 2016) and frequent meetings (every 1-2 months) would provide sufficient time to review and consolidate information in an informed process for updating the 2015 GHGI (that would be published in April 2017) and beyond.

Commenter: Giles Ragsdale

Comment: My 2 cents - Figure ES-15 (I look at this figure every year) - I think the majority of people forget that when comparing current greenhouse gas emissions to 1990, the population has risen steadily which drives demand for and emissions from most categories of greenhouse gases, e.g. electricity, transportation, etc. I think this figure tells a great story - emissions per capita are down to flat compared to 1990. I'd say EPA is doing good work that the general population does not recognize and some politicians chose to not recognize.

Commenter: Bridget Chadwick

Comment: Page 3-4:
Clarify the definition of energy as “the capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy)” [EIA Monthly Energy Review, MER] and identify the types of energy sources: fossil fuels, nuclear, and renewables. Emphasize that some fossil fuels are consumed for non-energy purposes (e.g. feedstock, reducing agents and non-energy products) but are inventoried separately in Section 3-2.

Comment: Page 3-7, Figure 3-4 U.S. Energy Consumption (Quadrillion Btu):
change the scale of the graph to provide more detail; (2) add gridlines so that energy consumption can be read more easily from the graph; (3) It appears that data for energy consumption + consumption of fossil fuels for non-energy use have been graphed with a peak of about 100 qBtu in 2007. From my estimates, using fossil fuel energy data provided in Table A-18 of EPA’s draft Inventory and nuclear and renewable energy provided in the EIA’s MER, total energy consumption in 2007 peaked at about 93.5 qBtu.

Comment: Pages ES-19, 3-6, 3-7 “In the United States, 82 percent of the energy consumed in 2014 was produced through the combustion of fossil fuels...” (page 3-6). :
From my estimates, in 2014, total fossil fuel energy amounted to 73.6794 qBtu (using data in Table A-11 of the EPA’s Inventory). Nuclear and renewable energy (including geothermal energy) and imported electricity amounted to 18.143 qBtu (using data in EIA’s February 2016 MER Tables 1.3 and 2.6). So fossil fuel energy was about 80% of total energy consumed in 2014. My calculation of energy consumption for specific energy sources will differ from EPA’s calculation, too.

Comment: Page 2-11, Figure 2-5: 2014 Energy Chapter Greenhouse Gas Sources (MMT CO2 Eq.):
The scale of the bar chart deemphasizes the significance of fossil fuel combustion. The scale should be expanded so that readers can see fossil fuel combustion produces the greatest portion (about 92%) of energy-chapter emissions. Furthermore, the adjacent piechart should show the breakdown of fossil fuel combustion in the energy chapter “slice”.

Comment: Page 2-3, “Energy-related CO2 emissions also depend on the type of fuel or energy consumed and its carbon (C) intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO2 emissions because of the lower C content of natural gas”. :
(1) Explain that the carbon intensity of an energy mix (e.g. electricity) is the energy-weighted average of the CO2 emission factors of the energy sources in the mix; (2) Provide a table of CO2 emission factors for all energy sources including nuclear and renewable energy and/or refer readers to Table A-39.

Comment: Page 3-14, (a) “Recently an increase in the carbon intensity of fuels consumed to generate electricity has occurred due to an increase in coal consumption, and decreased natural gas consumption and other generation sources”. (b) “Total U.S. electricity generators used natural gas for approximately 27 percent of their total energy requirements in 2014 (EIA 14" 2015b)”. :
Please correct the above statements: (a) Using the EPA Inventory for fossil fuel data (Table A-11) and the EIA MER (Table 2.6) for C-free/neutral energy data, the c-intensity of electricity has DECREASED steadily since 2005, from 60.579 MtCO2/qBtu in 2005 to 52.785 MtCO2/qBtu in 2014. (b) In 2014, natural gas was 22% of the total primary energy consumed for generating electricity and C-free/neutral energy was 35% of the total primary energy.

Supplemental Material Received

Appendix A

Appendix A from the University of Illinois at Chicago comment on the U.S. Greenhouse Gas Emissions and Sinks: 1990-2014

Appendix B

Appendix B from the University of Illinois at Chicago comment on the U.S. Greenhouse Gas Emissions and Sinks: 1990-2014

Appendix C

Appendix API comments on EPA's Memos on the updates being considered for the Transmission and Storage, the Production and the Gathering and Boosting segments of the Petroleum and Natural Gas Systems Sector in the GHG Inventory from the American Petroleum Institute comment on the U.S. Greenhouse Gas Emissions and Sinks: 1990-2014

Appendix D

Appendix API Comments on Updates under Consideration for Natural Gas and Petroleum Production Emissions, and Gathering and Boosting Emissions from the American Petroleum Institute comment on the U.S. Greenhouse Gas Emissions and Sinks: 1990-2014

Appendix A

APPENDIX A.
Shortcomings of current IPCC (2006) methodology for landfill methane emissions.

To summarize the shortcomings of the current IPCC (2006) model, below are listed the major deficiencies with supporting references and datasets:

- This model was never systematically field-validated for CH_4 emissions. Rather, the historic “validation” consisted of comparing *measured recovery* to *modeled generation* at 9 Dutch landfill sites (Oonk & Boom, 1995; Van Zanten and Scheepers, 1995; Oonk, 2010)

- Model results do not systematically replicate results from a growing database of field measurements for CH_4 emissions (Spokas et al., 2011, 2015; Bogner et al., 2010, 2011, 2016).

- GHG inventories [e.g., California GHG inventory] often do not consider actual landfill gas recovery data at specific sites, only an assigned “recovery efficiency” percentage applied to modeled generation. Typically, the assigned landfill gas recovery can differ substantially in both magnitude and direction (+ or -) from measured recovery. (Bogner et al., 2010, 2016)

- Actual measured landfill gas recovery can be directly related related to waste in place (WIP) using a simple linear relationship. Fig. 1 below demonstrates this relationship for 129 California sites using data from Walker et al., (2012). The relationship shown in this figure was independent of climate, status (open or closed), age, or size (WIP).

  Historical Note: In general, landfill gas modeling began in California during the mid-1970’s at the time of the first commercial landfill gas utilization projects. Then, At that time, a multiplicity of site-specific models were applied to the early project sites in order to predict future LFG recovery from waste-in-place (WIP), climate, waste composition, and other factors. [See further discussion in Findakakis and Leckie, 1979; EMCON, 1980; Halvadakis et al., 1983; Findakakis et al., 1988.] In those days, the choice of a particular model format for a specific site depended on optimizing the match between *predicted* annual LFG recovery and *actual* LFG recovery from the monitoring data available at that time. The models ranged from simple empirical relationships to complex, multicomponent multiphase kinetic models, some with lag times prior to the initiation of LFG generation. For the kinetic models, there was no unique solution for a specific site as multiple parameters were adjusted to improve model fit. The kinetic models (IPCC, 2006; LandGEM) were primarily adapted from the anaerobic digestion literature and accelerated laboratory decomposition studies on the premise that, conceptually, the annual mass of waste buried in a landfill may degrade similarly to waste in a digester but over longer timeframes.

  What might be a better idealized model for landfill biodegradation? Landfills also have significantly lower liquid contents than even “dry” or high solids digestion systems and, indeed, would be impossible to manage if digester values were applied to field settings. Taking a broader view, a better analogy for landfills is comparison to terrestrially-derived organic matter buried at shallow depths over longer-term "geologic" timescales. Initially, after burial, some portion of the organic carbon undergoes anaerobic decomposition with biogas generation. However, a significant portion of the organic carbon in the buried waste does not degrade over decadal timeframes (Bogner, 1992; Barlaz, 1998) and is available for future transformations via deeper geologic burial under conditions of increased heat and pressure. That process is termed "diagenesis" with endpoints over geologic timescales expected to be similar to peaty/humic coal materials.

- In spite of variable waste input data and climate-related k values for LFG generation using IPCC (2006), the primary dependency for emissions is on waste-in-place (WIP). This can be demonstrated [Fig. 2 below] using the 2011 California GHG inventory data (372 full-scale landfill sites). [See also Spokas et al., 2015; Bogner et al. 2016.] Using this methodology, larger landfills [having high WIP] cannot reduce emissions below a certain threshold as defined by this relationship. Moreover, this relationship tends to reward larger sites with non-optimized gas recovery strategies [due to the relatively constant relationship for emissions to WIP]. Conversely, this relationship tends to reduce incentives for sites to improve gas recovery systems to achieve emission reductions as those reductions are not credited.

- As discussed above, the default assumption of 10% annual oxidation in IPCC (2006) is based on a single study at one landfill (Czepiel et al., 1996). *Oxidation is a variable*, not a constant, with unique seasonal trends in each cover soil at each site. [See discussion and data in Spokas et al., 2011; Spokas and Bogner, 2011; Bogner et al., 2011.]

- The 3 major drivers for emissions are excluded. These are:
    1) The area, composition, and thickness of *site-specific cover soils* as the major engineered barrier for emissions.
    2) Climate trends unique to both the specific global location (e.g, latitude/longitude) & individual cover soils with seasonally variable gaseous transport & CH_4 oxidation rates due to temporally and spatially variable soil moisture & temperature.
    3) The physical effect of the engineered LFG system to recover CH_4 and concurrently reduce soil gas CH_4 concentrations at the base of the cover, reducing the CH_4 concentration gradient and thus reducing diffusive flux [see Spokas et al., 2011].

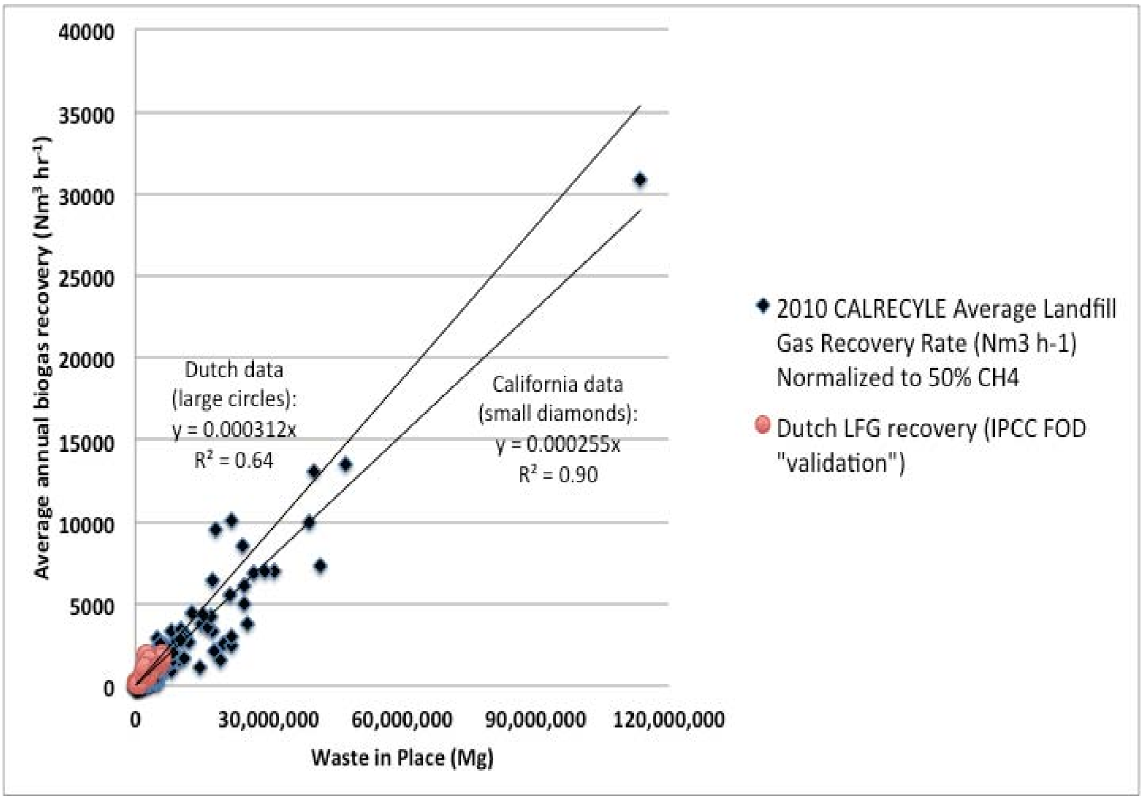


Fig. 1. Comparison between WIP and average biogas recovery rate for: *(a)* 2010 data from Calrecycles for 129 California sites (Walker et al., 2012): *blue diamonds*; and (b) IPCC FOD model field validation data from 9 Dutch landfills (1986-1993) (Oonk & Boom, 1995): *red circles.* Figure reprinted from Bogner et al., 2016.

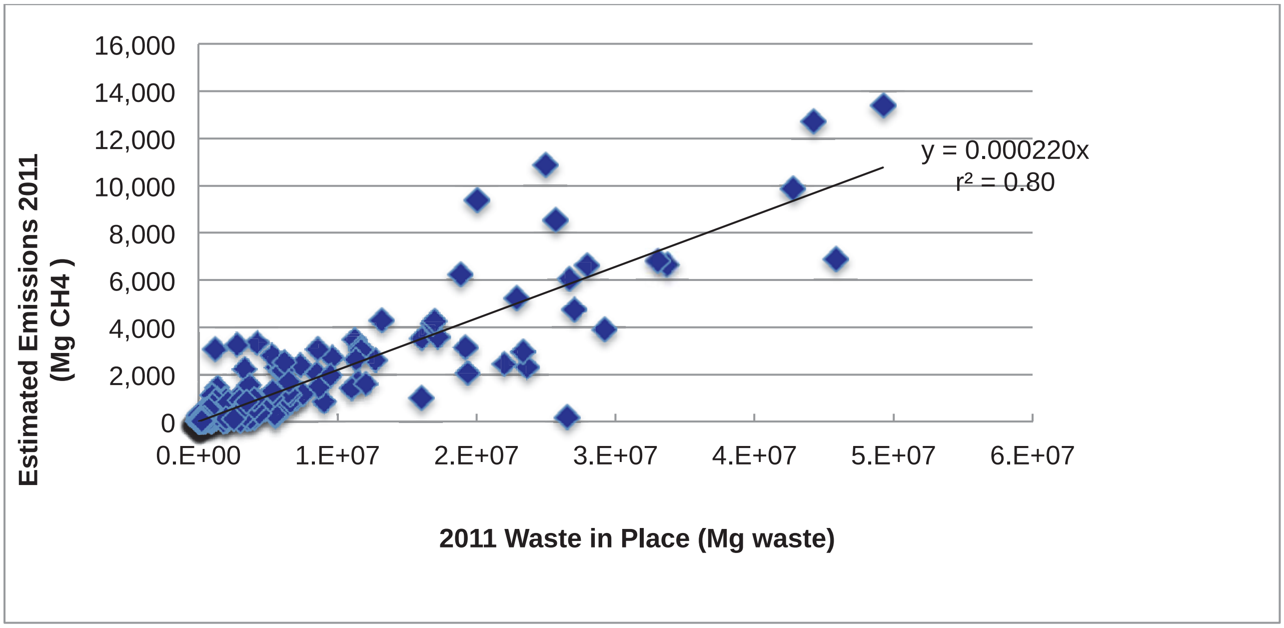
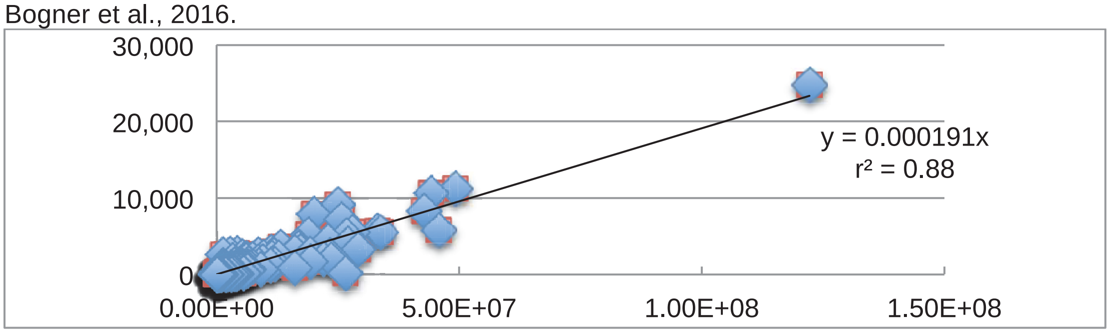


Fig. 2. (a) *ABOVE*: Relationship between estimated 2011 site-specific landfill CH_4 emissions using IPCC (2006) and WIP for 371 California landfills. (b) *BELOW*: Same relationship including the large Puente Hills Landfill [N=372]. Data from California Air Resources Board [ARB] (Hunsaker, 2012). NOTE: Predicted emissions from WIP using regression coefficients are 190-220 Mg CH_4/million Mg WIP. Figure reprinted from Bogner et al., 2016.



Appendix B

Appendix B.
Description and Overview of the CALMIM 5.4 Model.
[See Spokas et al., 2015; Bogner et al., 2014; Spokas et al., 2011; Spokas and Bogner, 2011; Bogner et al., 2011]

Developed over the last decade, CALMIM, or **CA**lifornia **L**andfill **M**ethane **I**nventory **M**odel, is a 1-dimensional finite difference model for the simultaneous simulation of heat, water, and gaseous transport through landfill cover soils. The model consists of a process-based methane *emissions* model which simulates emissions using 10-min time-steps and 2.5 cm depth increments in user-specified landfill cover materials at any global location. Table 1 at the end of this appendix provides an overview of the model structure, components and default boundary conditions. CALMIM is a freely available [www.ars.usda.gov] JAVA program which integrates site-specific data (location and cover design) with climatic simulation and one-dimensional soil microclimate and gas diffusion models for daily, intermediate, and final cover areas inclusive of CH_4 oxidation over a typical annual cycle. The model has proven to be user-friendly at sites where it has been applied to date (e.g., Cambaliza et al., 2015).

CALMIM includes: (1) the effect of engineered gas extraction; (2) the physical effect of daily, intermediate, and final cover materials to retard emissions; and (3) seasonal moisture and temperature effects on both gaseous transport and methanotrophic CH_4 oxidation in cover soils. The empirical relationship for oxidation used in the CALMIM model is derived from a series of over 900 laboratory incubations of landfill cover soils to determine relationships between methanotrophic activity and soil temperature & moisture (See Spokas and Bogner, 2011).

CALMIM was independently field-validated, first for v. 4.3 for California in the initial CALMIM project for the California Energy Commission [Bogner et al., 2011]. The original field validation for the CEC project (>800 measurements using static chambers) was conducted over two years on daily, intermediate, and final covers at two California sites, including the northern coastal Marina Landfill (Monterey County, CA) and the southern Scholl Canyon Landfill (Los Angeles County, CA). Also included were continuous measurements of soil temperature, moisture, and selected meteorological variables. Additional limited field validation was conducted for intermediate covers at the Lancaster, Kirby Canyon, and Tri-Cities Landfills through the cooperation of Waste Management, Inc. Oxidation was quantified through the use of a stable carbon isotopic method developed by J. Chanton which relies on the preference of CH_4–oxidizing microorganisms for the isotope of smaller mass (^{12}C) versus the heavier isotope (^{13}C). Subsequently, the improved CALMIM 5.4 developed under the EREF project was globally field-validated using 40 covers at 29 sites on 6 continents [Bogner et al., 2014], using data supplied directly by international research groups, published data, and data collected by the CALMIM team. A wide variety of methods (chamber, gradient, tracer, micrometeorological, vertical radial plume mapping, aircraft-based) were applied over scales ranging from <1m to km. CALMIM comparisons to field measurements resulted in a d-index of 0.765 using site-specific data (Willmott Index of Agreement; Wilmott, 1981), a Pearson r value > $|0.8|$ for modeled vs. measured comparisons at 25 of 29 sites, and an average mean error across all covers of 12 g CH_4 m^{-2} d^{-1}. Figure 3 below shows the main CALMIM input screen.

Figure 3. Main CALMIM input screen.

CALMIM estimates typical annual, site-specific landfill CH_4 emissions based on the respective areas and properties of daily, intermediate, and final cover materials, as well as the extent of engineered gas extraction. A major change from the IPCC (2006) method is that emissions are decoupled from a CH_4 generation model; instead, the emission processes at the top of the landfill are modeled directly. Another major change is that seasonal CH_4 oxidation is also modeled directly rather than relying on a % oxidation “default.” In terms of the IPCC structure, CALMIM is an IPCC “validated, higher quality” methodology for typical annual CH_4 emissions from landfills. CALMIM consists of four major integrated components:

(1) Data-Input Template;
(2) Meteorological Model;
(3) Soil Microclimate Model;
(4) 1-D Emissions/Oxidation Model.

With regard to (1), site locations are linked to latitude and longitude information. Input data are required on the surface area, thickness, and properties of the various cover materials for a particular site. Also, the extent of gas extraction and seasonal vegetation for each cover type are also required (both as % of surface area). With regard to (2) and (3), the meteorological and soil microclimate models rely on modified versions of the following globally-validated USDA models: Global TempSIM, Global RainSIM, Solarcalc, and STM^2. In particular, the soil temperature functions for STM^2 (Soil Temperature and Moisture^2) were modified to accommodate the landfill heat source. The latitude and longitude of the site are used to extrapolate the daily climatic conditions, as well as the soil microclimate conditions for 10-min. intervals for (minimum) 2.5-cm. depth increments for any landfill cover soil. With regard to (4), the emissions model is based on 1-dimensional diffusional transport of CH_4 and O_2 through each specified cover material.

The driving force is the CH_4 concentration gradient through the cover materials, which is dependent on the presence or absence of engineered gas recovery, the thickness and properties of the cover materials, and seasonal CH_4 oxidation rates. Methane oxidation is modeled through the use of scaled results relative to maximum rates for the full range of soil temperature and moisture conditions based on extensive laboratory studies for California landfill cover soils (>2000 incubations) and published literature. Oxidation is quantified by the difference in separate CALMIM model runs with and without oxidation for each cover type. CALMIM also calculates total annual site emissions by summing the emissions for all cover types. A standard substraction is also applied for O_2 uptake by heterotrophic respiration [competition for O_2 with CH_4 oxidation].

Below is shown (Fig. 4) some typical CALMIM output comparing 30 cm to 90 cm loamy sand intermediate covers at a southern California site. Note both the large variability in emissions at this site between the two thicknesses and differences for each thickness between the oxidized and unoxidized emissions. The highest emissions were associated with the mid-year dry season, diminishing in the later part of the year when the rainy season begins.

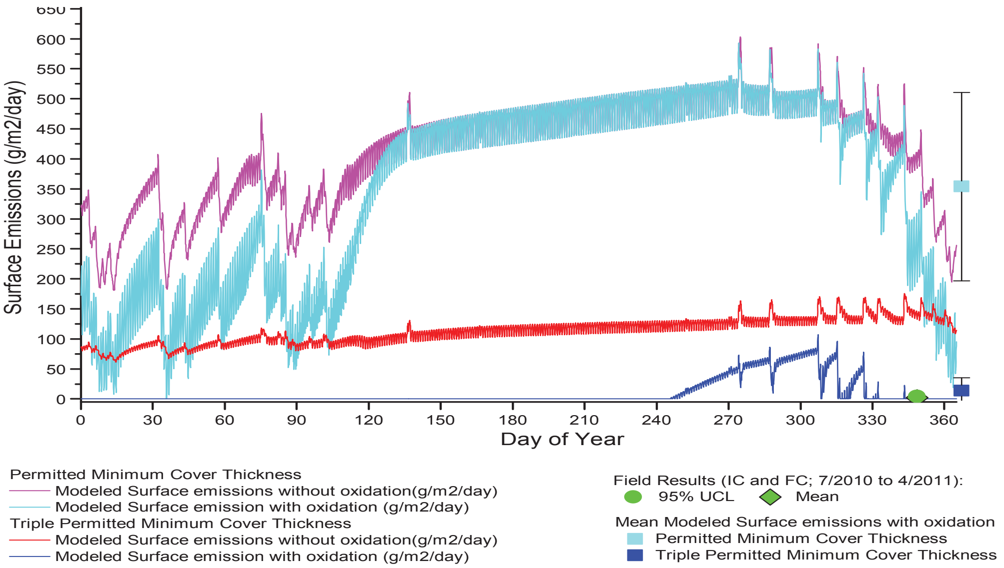


Fig. 4. Typical CALMIM output for southern California intermediate cover material. Comparison of 30 cm to 90 cm thickness over typical annual cycle. See text for additional explanation.

CALMIM relies on well-researched and accepted theoretical relationships, previous field and laboratory studies, existing globally-validated U.S. Dept. of Agriculture models, and extensive supporting laboratory studies on CH_4 oxidation using a variety of landfill cover soils over the full range of temperature and moisture conditions. Because the CALMIM model uses average climatic and soil microclimate data to calculate typical annual emissions, results may not be representative for atypical climate conditions (e.g., drought years) or where there are large differences in relief relative to regional weather stations. The site-specific application of CALMIM can be significantly improved through the use of "advanced" functions and site-specific data, including field measurement of the CH_4 concentration at the base of the cover.

To demonstrate the strong climate dependency of emissions, we remodeled the 2010 California landfill CH_4 emissions inventory for 372 sites using Calrecycles data from Walker (2012) and the field-validated CALMIM5.4 model (Spokas et al., 2015, Spokas et al., 2011), then compared the results to the existing 2010 California inventory from the California Air Resources Board (ARB) using the IPCC (2006) FOD model with regional California waste data and k values. See Fig. 5 below. It is important to note that the ARB method applies a 75% gas recovery efficiency to estimate the residual emissions, regardless of actual gas recovery. Importantly, the IPCC methodology does not consider either soil or climate drivers for gaseous transport nor seasonal methanotrophy in cover soils, allowing only the 10% annual oxidation per Czepiel et al. (1996 a,b).

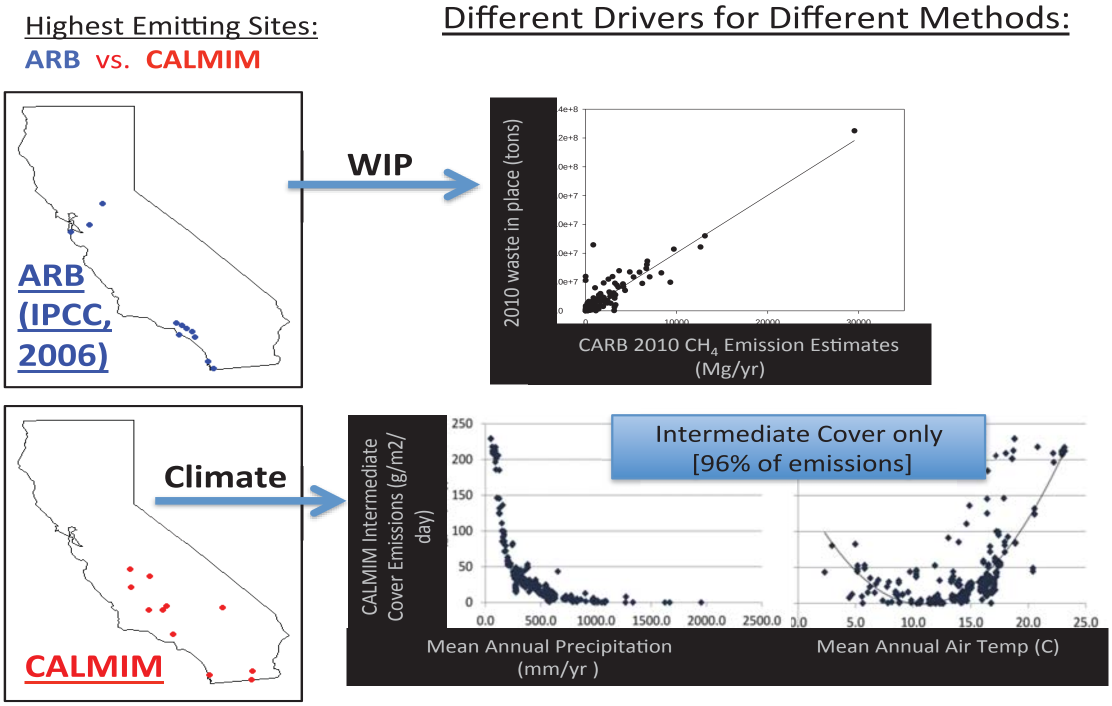


Fig. 5. Comparison of major dependencies for estimated California landfill CH_4 emissions using:
TOP: 2010 ARB inventory based on IPCC (2006) model showing dependency on WIP.
BOTTOM: 2010 inventory using CALMIM 5.4 showing dependency on climate for intermediate cover [96% of estimated state emissions]. Cover areas from Walker et al., (2012). The typical intermediate cover was modeled as 90 cm loamy sand with emission rates normalized to g CH_4 m^{-2} d^{-1}. See Spokas et al. (2015) for additional discussion and details. Also shown at left are the 11 highest emitting sites from each inventory.

Note that, in Fig. 5 the intermediate cover emissions for a typical 90 cm loamy sand are <20 g CH_4 m^{-2} d^{-1} when the mean annual precipitation (MAP) is >500 mm y^{-1}. Moreover, comparing the highest-emitting sites between the ARB and CALMIM inventories, those sites shift from landfills containing the largest mass of waste in the ARB inventory to sites with large areas of thinner intermediate cover and reduced oxidation rates during the annual cycle (e.g., too hot, too dry). These climate dependencies have important implications for developing more realistic, science-based GHG inventories for landfill CH_4.

Finally, we also directly compared CALMIM modeling using site-specific inputs for cover materials and areas to field measurements at 10 California sites [Fig. 6]. Field methods ranged from meter to kilometer scales, including chamber techniques, vertical radial plume mapping (VRPM), and aircraft plume methods. In this figure, we show standard CALMIM outputs for CH_4 emissions with oxidation and CH_4 emissions without oxidation for a “typical annual cycle” of 365 days. The plots shown in this figure include both single cover materials and whole site measurements over several years, depending on the methodology, scale, and date of the individual campaigns cited in the figure caption. See Spokas et al. (2015), Bogner et al. (2014), and references cited therein for additional details.

In Fig. 6., please also note the high seasonal variability and the large seasonal differences between the upper blue lines (emissions without oxidation) and the lower black lines (emissions with oxidation). Especially note that the lines for emissions with and without oxidation become merged at several sites during the mid- to late-year dry season due to negligible oxidation (too hot, too dry). Thus, modeled emissions inclusive of oxidation readily respond to dynamic soil moisture and temperature effects on oxidation rates during an annual cycle. Moreover, when examining results from any short-term field measurement campaigns at a specific global location, it is important to consider those results within the larger expected temporal variability of emissions over an annual cycle. In short, consistent with other soil sources of CH_4, climate effects on both oxidation and gaseous transport can vary greatly between cover soils at any one site, as well as seasonally and spatially between sites (Cambaliza et al., 2015).

In general, the CALMIM modeled emissions align with the field values and, as a minimum, are within the same order of magnitude. Differences can be attributed mainly to: (1) cover thickness and/or composition not modeled correctly (may not be rigorously tracked at specific sites except to confirm “permitted minimum” thickness or materials); (2) whether daily cover area emissions were realistically modeled (i.e., whether the working area overlies new waste only with expected low fluxes or fully methanogenic older waste driving high fluxes, with or without gas recovery); and (3) annual weather variability compared to 30-year average weather with 0.5 degree reliability.

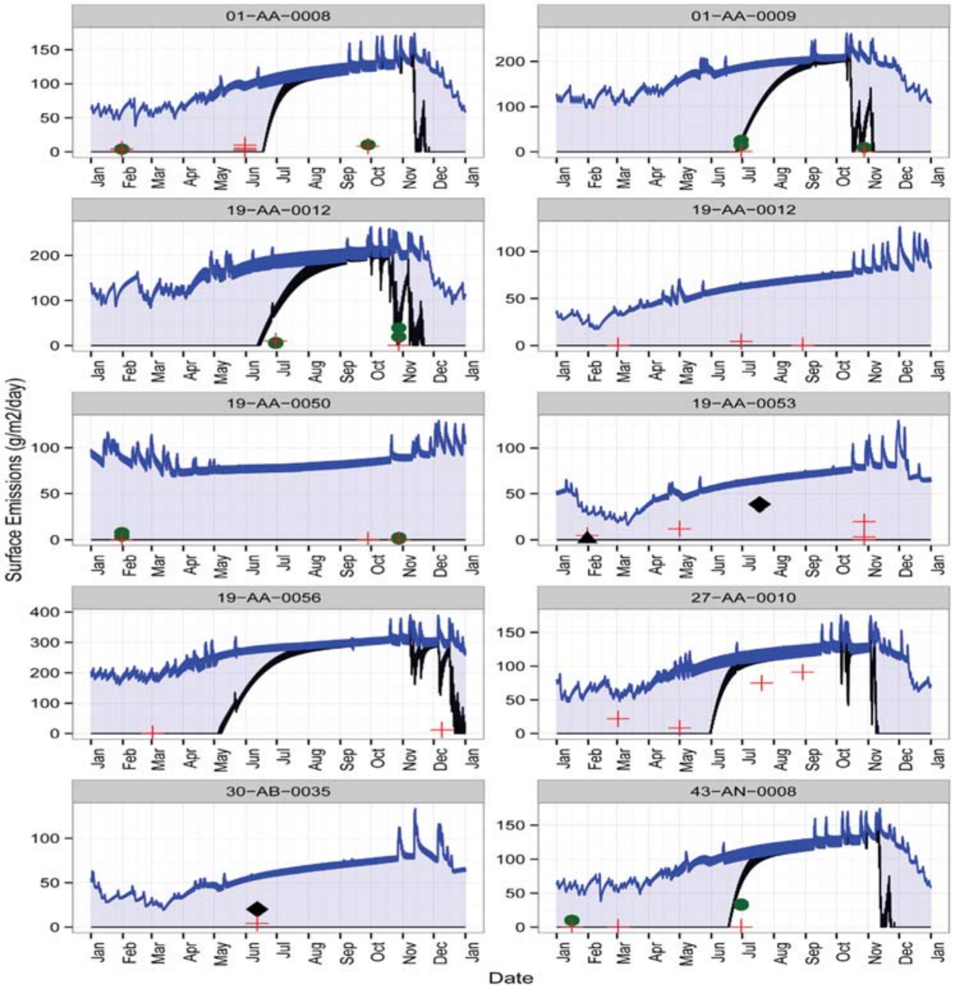


Figure 6. TOP: Comparison of typical annual cycle of emissions using CALMIM at 10 California sites to field measurements using a variety of techniques. CALMIM results indicate the "typical annual cycle" of 365 days where the black line is predicted emissions with soil oxidation and the blue line represents surface emissions without oxidation. The region between is shaded in light blue. Field results are plotted for the month of the measurement using different symbols for different techniques: Red plus sign indicates surface chambers (Spokas et al, 2011; Shan et al, 2012), black diamond/triangles indicates aircraft plume measurements (Peischl et al, 2013; Tratt et al, 2014), and the green circle indicates vertical radial plume mapping [VRPM] methods (Goldsmith et al, 2012). All units are g CH_4 m^{-2} d^{-1}. Figure reproduced from Spokas et al., 2015; please consult for further details. BOTTOM: Location map for California sites.

CALMIM is written entirely in JAVA and currently consists of 531 Java Classes and is written in the NetBeans Integrated Developer Environment (IDE). NetBeans IDE and NetBeans Platform are based on software from netbeans.org, which has been dual licensed under the Common Development and Distribution License (CDDL) and the GNU General Public License Version 2 with Classpath exception. For more information, please visit www.netbeans.org.

CALMIM uses a total of 21 integrated libraries, with the most significant ones being:

- **jFreeChart** – Provides the graphical display of the generated data - see http://www.jfree.org/
- **Liquid-Look-n-Feel** – Overall look-n-feel of the program
- **PTPLOT 5.6** – plotting program to display data - http://ptolemy.eecs.berkeley.edu/java/ptplot/
- **NanoXML** – Embedded XML parser for the CMM preference files http://nanoxml.sourceforge.net/orig/
- **XStream** – simple library to aid in saving and loading XML class library files (CMM preference file) - http://xstream.codehaus.org/
- **MigLayout** – layout manager for GUI windows http://miglayout.com/

As stated above, CALMIM is a 1-dimensional finite difference model for the simultaneous simulation of heat, water, and gas transport through the landfill soil cover. Table 1 below provides an overview of the model structure, components and default boundary conditions:

Table 1. Overview of CALMIM input parameters, bundled models, and outputs.

			Description		**Value/Units/Reference**
Model Inputs	Site		Latitude		Decimal degrees (+N , -S)
			Longitude		Decimal degrees (-W, +E)
			Waste Footprint		Acres
	Cover Characteristics		Coverage		0-100% of waste footprint
			Organic Matter		Low-high (0-5%)
			Vegetation Presence		0-100% cover (slider bar) Modifies incoming solar radiation [Si = (1-Veg%)*Si]
			Gas Recovery System		0-100% coverage (slider bar) Reduces the lower methane concentration in default cover scenarios
		Cover Type Selection			
		Daily	Temperature	Upper	Air temperature simulation
				Lower	25 °C
			CH_4	Upper	2 ppmv
				Lower	0.3 % (v/v)
			Oxygen	Upper	20 % (v/v)
				Lower	5 % (v/v)
			CH_4 oxidation rate		400 μg CH_4 $g_{soil}^{-1}d^{-1}$
		Intermediate	Temperature	Upper	Air temperature simulation
				Lower	35 °C

		CH_4	Upper	2 ppmv
			Lower	45 % (v/v)
		Oxygen	Upper	20 % (v/v)
			Lower	1 % (v/v)
		CH_4 oxidation rate		400 µg CH_4 $g_{soil}^{-1}d^{-1}$
	Final	Temperature	Upper	Air temperature simulation
			Lower	40 ^{o}C
		CH_4	Upper	2 ppmv
			Lower	55 % (v/v)
		Oxygen	Upper	20 % (v/v)
			Lower	0 % (v/v)
		CH_4 oxidation rate		400 µg CH_4 $g_{soil}^{-1}d^{-1}$
	Custom	User selectable boundary conditions		
Layer Characteristics		Material		Various materials (Table 2)
		Thickness		Variable: 2.5 cm to 2.5 m (1 to 100”)

Table 1. (Continued)

		Description		Value/Units/Reference
Bundled Models	GlobalTempSIM	Air temperature simulation		Spokas and Forcella, 2009
	GlobalRainSIM	Precipitation simulation		Spokas and Forcella, 2009
	SolarCalc	Solar radiation simulation		Spokas and Forcella, 2006
	STM[2]	Soil temperature and moisture model		Spokas and Forcella, 2009
	Gas Diffusion	Oxygen and methane diffusion		Campbell, 1985
Model Outputs	*Model outputs are written directly to Excel compatible files for each cover type*			
	Daily Surface CH_4 emissions	With oxidation		g CH_4 $m^{-2}d^{-1}$
		Without oxidation		g CH_4 $m^{-2}d^{-1}$
	Soil Nodes (2.5 cm layer in cover)	Soil Temperature		^oC
		Soil Moisture		Volumetric (cm^3 cm^{-3})
		Air-filled porosity		cm^3 cm^{-3}
		Oxygen Concentration		% O_2
		CH_4 Concentration	With oxidation	% CH_4
			Without oxidation	% CH_4
		CH_4 oxidation rate		g CH_4 $m^{-2}d^{-1}$
		CH_4 oxidation percentage		%
		Bulk density		g cm^{-3}
		Fraction of time oxidizing		0 to 100% (0-1)
	Simulated Weather Data	Maximum air temperature		^{o}C
		Minimum air temperature		^{o}C
		Precipitation		mm

References Cited: Letter and Appendices A & B:

Barlaz, M.A. 1998, Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills, Global Biogeochemical Cycles, 12, 373-380.

Bogner, J.E., 1992, Anaerobic Burial of Refuse in Landfills: Increased Atmospheric Methane and Implications for Increased Carbon Storage, Ecological Bull. 42:98-108.

Bogner, J.E., and Spokas, K.A., 2016, No More California Dreaming: Realistic Modeling of Landfill Methane Generation and Emissions Inclusive of Climate. Extended abstract for Global Waste Management Symposium, Indian Wells, California.

Bogner, J.E., Spokas, K.A., Chanton, J.P., 2011, Seasonal greenhouse gas emissions (methane, carbon dioxide, nitrous oxide) from engineered landfills: Daily, intermediate, and final California cover soils. *J. Environmental Quality,* 40, 1010-1020.

Bogner, J.E., Spokas, K.A., Chanton, J.P., 2010, CALMIM: California Landfill Methane Inventory Model - A New Field-Validated Inventory Methodology for Landfill Methane Emissions, Final Report to California Energy Commission Public Interest Energy Research Program, Contract No. 500-05-039, G. Franco, Program Manager. September 2010. 96 p.

Bogner, J., Spokas, K., and Corcoran, M., 2014, *International Field Validation of CALMIM: A Site-Specific Process-Based Model for Landfill Methane (CH_4) Emissions Inclusive of Seasonal CH_4 Oxidation,* Final Report to Environmental Research and Education Foundation (EREF), 406 p. Available at *http://erefdn.org/index.php/grants/fundedresearchinfo/international_field_validation_of_a_new_ipcc_model_for_landfill_methane_emi/.*

Cambaliza, M.O., Shepson, P.B., Bogner, J., Daulton, D., Stirm, B., Sweeney, C., Montzka, S., Gurney, K., Spokas, K., Salmon, O., Lavoie, T., Hendricks, A., Mays, K., Turnbull, J., Miller, B., Lauvaux, T., Davis, K., Karion, A., Moser, B., Miller, C., Obermeyer, C., Whetstone, J., Prasad, K., Crosson, E., Miles, N., and Richardson, S., 2015, Quantification and source apportionment of the methane emission flux from the city of Indianapolis, *Elementa: Science of the Anthropocene,* 3, paper 000037, doi: 10.12952/journal.elementa.000037. Available at: *https://www.elementascience.org/articles/37/*

Campbell, G.S., 1985, Soil Physics with Basic: Transport Models for Soil-Plant Systems, Elsevier, NY. 150 p.

Czepiel, P., Mosher, B., Crill, P., Harriss, R., 1996a. Quantifying the effect of oxidation on landfill methane emissions. Journal of Geophysical Research: Atmospheres (1984–2012) 101, 16721-16729.

Czepiel, P., Mosher, B., Harriss, R., et al., 1996b. Landfill methane emissions measured by enclosure and atmospheric tracer methods, Journal of Geophysical Research: Atmospheres (1984–2012) 101, 16711-16719.

EMCON, 1980, *Methane Generation and Recovery from Landfills*. Ann Arbor Science, Ann Arbor, MI, USA, CRC Press, 150 p.

Findikakis, A. N. and J. O. Leckie, 1979, Numerical simulation of gas flow in sanitary landfills, *J. Environ. Eng,* 105, 927-945.

Findikakis, A. N., C. Papelis, C. P. Halvadakis, and J. O. Leckie, 1988, Modeling gas production in managed sanitary landfills, *Waste Manage. Res.* 6, 115-123.

Halvadakis, C.P., Robertson, A.P., and Leckie, J.O., 1983, *Landfill Methanogenesis: Literature Review and Critique*. Stanford University Dept. of Civil Engineering, Environmental Engineering and Science Technical Report No. 271. Supported by Pacific Gas & Electric and Southern California Gas Co., 157 p.

Hunsaker, L., 2012, Site-specific California landfill CH_4 emissions inventory database 2009-2011. EXCEL Spreadsheet.

IPCC, 1996, 2006, *National GHG Inventory Guidelines Vol 5: Waste*. Available at: *http://www.ipcc-nggip.iges.or.jp/public.*

Oonk, H., 2010. *Literature Review: Methane From Landfills—Methods To Quantify Generation, Oxidation, and Emissions*. Report for the Sustainable Landfill Foundation. Assendelft, Netherlands.

Oonk H, and Boom T. 1995. Validation of landfill gas formation models. *Studies in Environmental Science* 65, 597–602.

Peischl, J., Ryerson, T., Brioude, J., Aikin, K., Andrews, A., Atlas, E., Blake, D., Daube, B., Gouw, J., Dlugokencky, E., 2013. Quantifying sources of methane using light alkanes in the Los Angeles basin, California. J. Geophysical Research: Atmospheres, 118, No. 10 27, 4974–4990.

Scheutz, C., Kjeldsen, P., Bogner, J., deVisscher, A., Gebert, J., Hilger, H., Huber-Humer, M., and Spokas, K., 2009, Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions, *Waste Management and Research*, 27, 409-455.

Shan, J., Jacoboni, M., and Ferrante, R., 2013, Estimating greenhouse gas emissions from three Southern California landfill sites. *Proceedings 2013 SWANA Landfill Gas Symposium*. Published by SWANA, Silver Spring, MD.

Spokas, K., and Bogner, J., 2011, Limits and dynamics of methane oxidation in landfill cover soils, *Waste Management* 31, 823-832.

Spokas, K., Bogner, J., and Chanton, J., 2011, A process-based inventory model for landfill CH_4 emissions inclusive of soil microclimate and seasonal methane oxidation, *J. Geophys. Research Biogeosciences,* 116, paper G04017.

Spokas K, Bogner J, Corcoran M, and Walker S., 2015, From California dreaming to California data: Challenging historic models for landfill CH_4 emissions. *Elementa: Science* *of the Anthropocene, 3,* paper 000051, doi: 10.12952/journal.elementa.000051. Available at: *https://www.elementascience.org/articles/51/*

Spokas, K., and Forcella, F. 2006. Estimating Hourly Incoming Solar Radiation from Limited Meteorological Data. Weed Science 54: 182-189.

Spokas, K. and F. Forcella, F. 2009. Software Tools for Weed Seed Germination Modeling. Weed Science 57, 216–227.

Tratt, D. M., Buckland, K.N., Hall, J.L., Johnson, P.D., Keim, E. R., et al., 2014, Airborne visualization and quantification of discreet methane sources in the environment, *Remote Sens. Environ*., 154, 74-88.

.

van Zanten, B. and Scheepers, M., 1995, Modeling of Landfill Gas Potentials. In *Proceedings from the SWANA 18'" Annual Landfill Gas Symposium*, New Orleans, LA, published by SWANA, Silver Spring, MD.

Walker, S., et al., 2012,, California Dept. of Resource Recovery & Recycling. EXCEL Database: Landfill Data Compilation. With the assistance of W. Gin (Senior Eng.; deceased), M. Holmes, and H. Hansra,

Willmott, C.J., 1981, On the validation of models, *Physical geography* 2, 184-194.

Appendix C

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Re: Updates under Consideration for Natural Gas Transmission and Storage Segment Emissions in the 1990-2014 GHG Inventory

Dear Melissa,

The American Petroleum Institute (API) appreciates the opportunity to provide comments on proposed updates to the 1990-2014 U.S. Greenhouse Gas (GHG) inventory for the Natural Gas Transmission and Storage segment.

API continues to compile and analyze emissions data for petroleum and natural gas operations and is open to working with EPA on utilizing data provided through EPA's mandatory GHG reporting program (GHGRP). API has provided comments and recommendations to the U.S. EPA on the draft Natural Gas Systems and Petroleum Systems sections of the national inventory since 2002, including at the recent stakeholder workshop in November 2015 regarding GHG data for Petroleum and Natural Gas Systems.

For this current review, API provides general comments and also addresses several specific questions raised in EPA's transmission and storage memo. Our review, however, is limited due to the short response time, overlapping comment periods for other proposed changes to the GHGRP, and the approaching March deadline for reporting 2015 GHGRP data.

General Comments

EPA's proposed updates for compressor station components rely primarily on two studies published by Colorado State University in 2015[1] [2]. Substantial new data are available from measurements at

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[1] Subramanian, R.; Williams, L.L.; Vaughn, T.L.; Zimmerle, D.; Roscioli, J.R.; Herndon, S.C.; Yacovitch, T.I.; Floerchinger, C.; Tkacik, D.S.; Mitchell, A.L.; Sullivan, M.R.; Dallmann, T.R; Robinson, A.L. Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol. Environmental Science and Technology, 49, 3252-3261. 2015.

transmission and storage compressor stations that report through Subpart W. API agrees that updated GHGI emissions data are warranted and as such recommends that EPA form a multi-stakeholder working group comprised of industry, governmental, and environmental organizations active in GHG emissions measurements and estimates to evaluate recently published data that may be used for updating the national GHG inventory. API proposes that such a working group be convened following the completion of the 2014 GHGI to provide a structured framework for consultation and review of GHGI updates. An early start (April 2016) and frequent meetings (every 1-2 months) would provide sufficient time to review and consolidate information in an informed process for updating the 2015 GHGI and beyond.

API reiterates that the EPA should carefully analyze and screen GHGRP reported data in order to improve the validity of data used in the national GHGI. Obvious data errors and/or outliers should be assessed, corrected or excluded to prevent disproportionately impacting the derivation of emission factors (EFs) or extrapolation of information for the national GHGI.

Responses to EPA Questions

Transmission and Storage Station Fugitive Emissions

- ✓ (Question #1 from EPA's memo) As EPA considers options for applying EFs for this source, the EPA seeks stakeholder feedback on the timing of changes in transmission and storage stations non-compressor fugitive sources that may result in different emissions in recent years from those in the GRI/EPA study. The EPA could use GRI/EPA factors for earlier years in the time series, and Zimmerle factors for more recent years. Alternatively, the EPA could apply the Zimmerle EF to all years of the GHGI time series. The EPA seeks stakeholder feedback on these options.

API Comment: GRI/EPA emission factors should be used for initial estimates in the time series and EPA should use updated emission factors for the current estimate.

- ✓ (Question #3 from EPA's memo) The EPA seeks stakeholder feedback on how to incorporate information on super emitters into estimates for transmission and storage stations. For example, the Zimmerle study estimated a fraction of the population that may be super emitters at a given time, and estimated super emitter emissions from these sources (incremental to those estimated for the non-super emitter population). The EPA also seeks stakeholder feedback on which GHGI sources are more likely than others to act as super emitters and whether and how to apply a super emitter factor or other methodology to those sources.

API Comment: Recent measurement studies have shown skewed "long tail" distributions for source level measurements, where a few emission sources may contribute a disproportionately high fraction of emissions. As the Zimmerle study points out, large data sets are needed to accurately characterize the "long tail" distributions. Although the Subramanian study contributes new measurement data for 45 compressor and storage stations, it represents just a

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[2] Zimmerle, D.J.; Williams L.L.; Vaughn, T.L.; Quinn, C.; Subramanian, R.; Duggan, G.P.; Willson, B.; Opsomer, J.D.; Marchese, A.J.; Martinez D.M.; Robinson, A.L. Methane Emissions from the Natural Gas Transmission and Storage System in the United States. Environmental Science and Technology, 49, 9374-9383. 2015.

subset of all measurements conducted as part of Subpart W reporting, which provides a substantially larger data set of emissions that are characteristic of the entire distribution.

As the Zimmerle study indicates, the identified "super emitters" fraction of the population is dynamic and may vary each time a measurement is taken. Therefore the approach being proposed by EPA in the question – which implies that EPA is considering to separately adjust the national inventory for super-emitters – is not appropriate for extrapolation of the data to the national GHGI. This approach would be incorrect and would essentially double count the effect of super-emitters since they are already accounted for in the Zimmerle emission factors and in the Subpart W reported data.

The Pipeline Research Council International (PRCI) is conducting a research project to compile and analyze Subpart W data. The dataset includes 2011 through 2013 measurement data collected from members who have also provided supplemental data on equipment, operations, and measurement methods. Although a subset of data reported to EPA, it represents well over half of the reporting facilities. These measurement data should be assessed and can be used to calculate compressor station emission factors and evaluate the frequency and size of the larger leaks from key sources – compressor seals, compressor valves and storage tank dump valves. The report is expected to be available in the second quarter of 2016.

API advises that an alternative approach would be to develop new average emission factors that integrate data from both the recent measurement study results and Subpart W measurements. Such average emission factors should incorporate the range of emissions observed in current operations without artificially superimposing on them a "super emitter" adjustment which is highly uncertain. The emission factors should be updated periodically based on additional Subpart W data that become available with each future reporting year and potentially new, relevant and independent measurement programs.

- ✓ (Question #4 from EPA's memo) The EPA seeks stakeholder feedback on how to incorporate Subpart W data into the GHGI methodology, such that the transmission station and storage station activity data (AD) and/or EFs would be updated annually to reflect ongoing trends in the industry. For example, the EPA could consider combining the Zimmerle et al. data and Subpart W data in some way.

API Comment: A significant amount of information is reported to EPA through Subpart W. EPA now has four years of fugitive measurement data for specific emission sources and activity data regarding the distribution of centrifugal versus reciprocating compressors as well as the fraction of wet seal versus dry seal centrifugal compressors. API encourages EPA to make use of this information and integrate Subpart W based emission factors as an update to the GHGI. Activity data and emission factors should be updated periodically based on additional Subpart W data that become available with each future reporting year and potentially new, relevant, and independent measurement programs.

EPA's memo on revisions under consideration for transmission and storage emissions indicates that EPA intends to use the emission factors for compressor fugitive emissions, non-compressor fugitive emissions, and pneumatic controllers from the Zimmerle study. API supports the use of this recent measurement data, which accounts for the presence and random nature of super-emitters. However, API strongly encourages EPA to also make use of the substantial amount of measurement data available from Subpart W. The PRCI report is an example of additional information that should be considered by EPA and a multi-stakeholder workgroup.

- ✓ (Question #5 from EPA's memo) In fall 2015, a well in a California storage field began leaking methane at an estimated rate of 50 Mt CH4 per day. The EPA is considering how to include this emission source in its 2017 GHGI (with estimates from 1990-2015). For example, the EPA could review and potentially incorporate estimates of the leak developed by the California Air Resources Board (CARB).

API Comment: The storage field leak in California is a one-off failure event. If EPA believes the emissions from this event warrant inclusion in the 2015 national GHG emissions for Natural Gas Systems, then API contends that the emissions should be estimated for this single event with an annotation in the inventory which references the event and the emission estimation method. The emissions from this singular event should not be back-cast to prior years, nor should the emissions be projected to future years.

Reciprocating and Centrifugal Compressors

For Storage, EPA is not considering changes to the method used to count compressors. EPA plans to report a combined number and will not differentiate between reciprocating and centrifugal compressors to be consistent with planned updates to the emission factor. EPA's memo notes that the Zimmerle study found most storage stations employ reciprocating compressors. However, this is inconsistent with the Subramanian study which observed that the compressor type can impact emissions and centrifugal compressors have become much more common at transmission and storage stations. For compressor emission factors applied to Storage, API recommends utilizing storage station compressor measurement data reported for Subpart W to develop emission factors separately for reciprocating and centrifugal compressors, and also report compressor emissions separately by compressor type. This provides greater transparency and enables trends in compressor counts and emissions to be tracked over time.

Pneumatic Controllers

- ✓ (Question #11 from EPA's memo) The EPA seeks stakeholder feedback on use of the Zimmerle et al. estimates of pneumatic controller counts per transmission or storage station to develop national AD across the time series. For example, the EPA could use GRI/EPA pneumatic controller counts for earlier years in the time series and Zimmerle et al. counts for more recent years. Alternatively, the EPA could apply the Zimmerle et al. pneumatic controller counts to all years of the GHGI time series. The EPA seeks stakeholder feedback on these options.

API Comment: Subpart W provides a comprehensive, annual data set for determining the number of pneumatic controllers by station and the distribution by type of controller. API recommends using the Subpart W activity data for recent years in the GHGI, the GRI/EPA data for early years in the time series, and interpolating between the two for intermediate inventory years rather than using activity data that is based on the Zimmerle or Subramanian study.

- ✓ (Question #13 from EPA's memo) The EPA seeks stakeholder feedback on approaches to stratify pneumatic controller estimates into specific bleed rate categories (e.g., basing AD on the number of low-bleed, intermittent bleed, and high bleed devices and applying an EF specific to each type). For example, the EPA could use the Subpart W data on the number of pneumatic controllers of specific controller types per station, and their associated specific EFs. In addition, the EPA seeks comment on use of GHGRP data to represent national transmission and storage station pneumatic controller activity and emissions.

API Comment: API recognizes that the stratification of pneumatic controllers into specific bleed rate categories can be challenging. API has recently engaged in technical assessments of pneumatic controllers' categories and their leakage vs. engineered venting characteristics[3]. Over the past year, through API's standard development process including a stakeholders group, API has been working to establish a process for categorizing properly functioning pneumatic controllers and to address fugitive emissions from mal-functioning controllers. API hopes that this standard, when complete, will go a long way towards addressing the issue raised by EPA above.

Hi-Flow Sampler Measurements

- ✓ (Question #14 from EPA's memo) Much of the available measurement data on transmission and storage segment emissions were developed using Hi-Flow Samplers. A recent study, Howard 2015, highlights potential malfunctions in certain Hi-Flow instruments under certain conditions that can lead to underestimates. The EPA is seeking stakeholder feedback on the impacts of the Hi-Flow sampler issue on the results of studies highlighted here and whether are there methods for recalculating some of the data points to correct for it.

API Comment: The Subramanian study showed good agreement between the concurrent site level emission source measurements and down-wind tracer flux measurements. The study report indicates that the dominant uncertainty in the study onsite estimate is due to uncharacterized emission sources (undetected or identified as inaccessible) rather than "parametric uncertainty associated with individual measurements or instruments." Based on this observation by the researcher/author, it might be concluded that the issues identified by Howard did not appear to have occurred in the measurements conducted during the Subramanian study.

The June 2015 article by Howard (Energy Science and Engineering 2015; 3(5):443–455, doi: 10.1002/ese3.81) focusses on measurements conducted in the production sector ("UT Phase 1" Study) and has drawn attention to a sensor response issue that may be averted to a large extent with a firmware update, careful calibration, and repeated quality control checks during the measurement process. Allen responded to Howard's article, providing information that extra steps were undertaken during to ensure the validity of the measurements from the UT Phase 1 study.[4]

The Hi-Flow instrument is one of a very few existing devices for cost-effectively quantifying natural gas emissions from fugitive and venting at the emission source, and it is an approved measurement device under Subpart W. As with any measurement device, uncertainties in measured data exist and the experience gained by additional field studies is enabling the

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[3] [Simpson, 2014] Pneumatic Controllers in Upstream Oil and Gas, *Oil & Gas Facilities Volume 3 Number 5,* October, 2014

[4] Allen, D.T., Sullivan, D.W., and Harrison, M. Response to Comment on "Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers", Environmental Science & Technology, 49, 3983-3984, doi: 10.1021/acs.est.5b00941 (2015).

research community to alert instrument manufacturers and industry to operation and calibration problems that ought to be fixed.

API's comments above are based on our long term engagement in reviewing and providing information for the U.S. GHG Inventory. It includes observations and recommendations for careful QA/QC of data extracted from the mandatory GHGRP to improve the validity and representativeness of data used for the U.S. GHG Inventory. We reiterate our recommendation for EPA to form a multi-stakeholder workgroup to discuss updating the national GHGI to incorporate information from recent measurement study results and Subpart W data.

API appreciates the opportunity to provide comments on the proposed revisions to the U.S. national GHG Inventory and EPA's willingness to work with industry to improve the data used for the national inventory. API encourages EPA to continue these collaborative discussions and is available to work with EPA to make best use of the information available under the GHGRP to improve the national emission inventory. We look forward to continuing our collaborative work in the GHGI development process.

Sincerely,

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Re: Updates under Consideration for Natural Gas and Petroleum Production Sector Emissions and Gathering and Boosting Emission in the 1990-2014 GHG Inventory

Dear Melissa,

The American Petroleum Institute (API) appreciates the opportunity to provide comments on proposed updates to the 1990-2014 U.S. Greenhouse Gas Inventory (GHGI) for the Natural Gas and Petroleum Production Sectors, and for Gathering and Boosting emissions.

API continues to compile and analyze emissions data for petroleum and natural gas operations and appreciates the opportunity to work with EPA on utilizing data provided through EPA's mandatory greenhouse gas reporting program (GHGRP). API has provided comments and recommendations to the U.S. EPA on the draft Natural Gas Systems and Petroleum Systems sections of the national inventory since 2002, including at the recent stakeholder workshop in November 2015 regarding greenhouse gas (GHG) data for Petroleum and Natural Gas Systems.

For this current review, API provides general comments and also addresses several specific questions raised in the two EPA memos:

- Inventory of U.S. Greenhouse Gas Emissions and Sinks: Revisions under Consideration for Natural Gas and Petroleum Production Emissions, February 2016; and
- Inventory of U.S. Greenhouse Gas Emissions and Sinks: Revisions under Consideration for Gathering and Boosting Emissions, February 2016.

Our review, however, is as comprehensive as is possible within the short response time, overlapping comment periods for other proposed changes to the GHGRP and the approaching March deadline for reporting 2015 GHGRP data. On top of our response to these memos, API intends to also comment on the "public review" version of the 1990-2014 preliminary Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks that was released on February 22, 2016.

General Comments

- EPA's current methodological updates for ***natural gas and petroleum production*** operations rely primarily on Subpart W reported activity data with a focus on fugitive emission sources and pneumatic devices. Of note is that the production memo does not address new measurement studies or updates that were previously outlined in two memos EPA issued in April 2015.[1,2]

- EPA's logic, presented in these memos appears inconsistent. First, EPA notes that Subpart W GHGRP data covers 32% of the active wellheads for 2013 and proposes to use this percentage to "scale" some emission sources to a national level. Simultaneously EPA states that the GHGRP Subpart W data covers the majority of national oil and natural gas production sources. Separately, EPA has also determined that Subpart W covers about 85% of the GHG emissions from the onshore oil and natural gas production sector - see the Subpart W Technical Support Document (Table 5, Threshold Analysis for Petroleum and Natural Gas industry Segment; https://www.epa.gov/sites/production/files/2015-05/documents/subpart-w_tsd.pdf). Clearly, if Subpart W covers 85% of the GHG emissions from this sector, then there is no basis for changing the GHGI in a manner that estimates 90% higher overall GHG emissions (based on the recalculated 2013 inventory). This discrepancy in GHGRP Subpart W emissions coverage must be fully explored and explained prior to making the proposed changes to derive GHG emissions in the GHGI for this sector. Given that the GHGRP Subpart W reported GHG emissions are substantially less than in the GHGI for 2013, the scaling to national GHG emissions for the GHGI should also be less than the 15% of emissions EPA previously determined are **not** covered by GHGRP Subpart W.

- EPA's methodological updates for ***Gathering and Boosting*** relies solely on data from the Mitchell et al.[3] and Marchese et al.[4] studies. However, the study focused on downwind, site-level ambient concentration measurements that are not appropriate nor designed to characterize activity data or emission factors for the Gathering and Boosting sector sources.

- API suggests that EPA review the work of Eben Thoma et al. with the EPA's Office of Research and Development (ORD) pertaining to off-site ambient concentration type studies, and the criteria necessary to obtain useful information from such a study as well as the limitations to the accuracy and usefulness of the information developed.[5] The conclusions are similar to the conclusions from an Australian government commissioned study conducted by CSIRO.[6] (For EPA's convenience, copies of both papers are provided in the appendix to these comments, beginning on page 20)

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[1] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: Potential Revisions to Liquids Unloading Emissions Estimate" April 2015.

[2] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: Potential Revisions to Pneumatic Controller Emissions Estimate (Production Segment)" April 2015.

[3] Mitchell, A. L.; Tkacik, D. S.; Roscioli, J. R.; Herndon, S. C.; Yacovitch, T. I.; Martinez, D. M.; Vaughn, T. L.; Williams, L.L.; Sullivan, M.R.; Floerchinger, C.; Omara, M.; Subramanian, R.; Zimmerle, D.; Marchese, A.J.; Robinson, A.L. Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results. Environmental Science & Technology, 49, 3219−3227. 2015.

[4] Marchese, A. J.; Vaughn, T. L.; Zimmerle, D.J.; Martinez, D.M.; Williams, L. L.; Robinson, A. L.; Mitchell, A. L.; Subramanian, R.; Tkacik, D. S.; Roscioli, J. R.; Herndon, S. C. Methane Emissions from United States Natural Gas Gathering and Processing. Environmental Science & Technology, 49, 10718-10727. 2015.

[5] Halley L. Brantley,†,# Eben D. Thoma,*,† William C. Squier,† Birnur B. Guven,‡ and David Lyon§; Assessment of Methane Emissions from Oil and Gas Production Pads using Mobile Measurements

[6] Day, S., Dell'Amico, Fry, R., Javanmard Tousi, H., (2014). Field Measurements of Fugitive Emissions from Equipment and Well Casings in Australian Coal Seam Gas Production Facilities. CSIRO, Australia

- API is concerned about EPA's intent to utilize the Mitchell et al. and Marchese et al. studies to develop a station-level emission factor which would significantly limit any evaluation of source-level emission trends over time. The small population size of the underlying Mitchell et al. study, the lack of emission source detail, and the numerous compounding assumptions made in the Marchese et al. study to "scale" the modeled results, may not provide sufficient certainty to use the study results for GHGI revisions to the Gathering and Boosting sector.

- Conversely, significant activity data will be available through the GHGRP in coming years. API urges EPA to delay significant revisions to the GHGI related to Gathering and Boosting until the GHGRP data are available. At that time, API recommends that EPA provide a separate accounting of activity data and emissions for Gathering and Boosting sources as a separate sector or as a subset of the Production sector.

- As stated previously in our comments on EPA's Transmission/Storage memo, API agrees that updated GHGI emissions data are warranted and as such recommends that EPA form a multi-stakeholder working group comprised of industry, governmental, and environmental organizations active in GHG emissions measurements and estimation to evaluate recently published data that may be used for updating the national GHG inventory. API proposes that such a working group be convened following the completion of the 2014 GHGI (April) to provide a structured framework for consultation and review of GHGI updates. An early start (April 2016) and frequent meetings (every 1-2 months) would provide sufficient time to review and consolidate information in an informed process for updating the 2015 GHGI and beyond.

- Additionally, API reiterates that the EPA should carefully analyze and screen GHGRP reported data in order to improve the validity of data used in the national GHGI. Obvious data errors and/or outliers should be assessed, corrected or excluded to prevent disproportionately impacting the derivation of emission factors (EFs) or extrapolation of information for the national GHGI.

Responses to EPA Questions for Revisions under Consideration for the Production Sector

General Use of Subpart W Data

- ✓ (Question #1 from EPA's Production memo) The EPA seeks feedback on how to take into account the reporting threshold when using Subpart W data, and the appropriateness of using Subpart W-based AFs for the national population of major equipment and pneumatic controllers.
    a. Are other data sources available that would help the EPA determine characteristics of the non-reporting population?
    b. Are other approaches available for scaling up this data for use in the GHGI?

API Comment: Although Subpart W does not capture all U.S. production operations, it is the most significant source of activity data available. We would expect that production operations not reporting through Subpart W are likely much smaller facilities, such as those associated with stripper wells. It is reasonable to expect a difference in major equipment and pneumatic controller counts in these smaller facilities compared to facilities that meet the Subpart W reporting threshold. However, sufficient information for major equipment and pneumatic controller counts, for emission estimates, is lacking for the facilities that fall below the reporting threshold. Therefore, although API supports EPA's use of information available through the GHGRP to update equipment counts in the national inventory, a note of caution is advised when using the GHGRP pneumatic device count to characterize stripper wells or other smaller production well types, which tend to typically have fewer, if any, pneumatic controllers for their operations. As a result, the use of activity factors (AFs) based solely on average reporting data in the GHGRP will likely over-estimate equipment counts from non-GHGRP wells.

In addition, estimates of the coverage of the GHGRP would be expected to be different in each production basin depending on the characteristics of ownership (many small operators vs. larger companies), historical development trends, and type of production in the region. For example, a recent analysis of available data in the Barnett Shale[7] in 2013 found that the oil and gas well count in the GHGRP (15,900 wells) only represented 46% of the well count (34,800) derived from GHGI methods. In that same study, the author estimated 29,900 oil and gas wells from other available data. This discrepancy highlights the need for more transparency in GHGI well count methods, as API has previously commented (see Question #7).

The correlation between GHGRP and GHGI well counts would be expected to be worse in other production regions since much of the Barnett Shale development[8] has occurred over the last 8 years for shale oil and gas production, which typically includes more on-site production equipment and may be more likely to be reported under the GHGRP. In addition, some operators have begun to move towards multi-well pads and shared production equipment for multiple wells. Properly-scaling GHGRP and other activity factors to a national level is a difficult technical challenge that will require substantial data analysis and a multi-stakeholder group for proper implementation. Such a group should be convened in order to ensure that future changes to the GHGI represent a true and robust national emissions estimate.

Furthermore, under the GHGRP, companies report devices that do not emit as typical pneumatic controllers so the population of controllers in the GHGRP data is very different than the population measured in the GRI/EPA study (conducted in 1992-1993 and published in 1996) and it is erroneous to take the count of all such devices and scale them up to the national inventory by using the wellhead count and the emission factors from the GRI/EPA study. For example, emergency shutdown devices (ESD) are largely designed to emit only during a process upset in order to shut-in production. Given the infrequency of this type of event, it would be improper to characterize these controllers in the same way as the continuous vent pneumatics that are assumed as part of current GHGI inventory factors.

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[7] Lyon, D.R., Zavala-Araiza, D., Alvarez, R A., Harriss, R., Palacios, V., Lan, X., Talbot, R., Lavoie, T., Shepson, T., Yacovitch, T. I., Herndon, S. C., Marchese, A.J., Zimmerle, D., Robinson, A. L. and Hamburg, S. P. *Constructing a spatially resolved methane emissions inventory for the Barnett Shale Region*, Environmental Science and Technology, **49**, 8147-8157, 2015

[8] http://www.rrc.state.tx.us/oil-gas/major-oil-gas-formations/barnett-shale-information/

- ✓ (Question #2 from EPA's Production memo) The EPA seeks feedback on other data sources (e.g., Allen et al. 2013 and 2014, the Prasino Group 2013) that could be considered for the development of emission factors for equipment leaks and/or pneumatic controllers.
    a. Allen et al. 2014 study did not differentiate between controller types. Is it possible to disaggregate the Allen emissions data in a way that would allow the EPA to calculate emissions for various control types?

API Comments on Pneumatic Controllers: API commented previously[9] that the emission factors used for quantifying pneumatic controller emissions, especially the intermittent-bleed controller factor, largely overestimates these emissions. Therefore, if EPA intends to update the count of pneumatic controllers in the national inventory then EPA must also in parallel (or at the same time) update the emission factors.

EPA's current memo outlining methodological changes under consideration for estimating methane (CH_4) emissions from production operations does not refer to, nor draw on information EPA presented in its April 2015 memo on potential revisions to pneumatic controller emission estimates[2]. In the April 2015 memo, EPA summarized the following studies:

- Allen, D.T., Pacsi, A., Sullivan, D., Zavala-Araiza, D., Harrison, M., Keen, K., Fraser, M., Hill, A.D., Sawyer, R.F., and Seinfeld, J.H., *Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers*, Environmental Science & Technology, 10.1021/es5040156.
- Oklahoma Independent Petroleum Association (OIPA), *Pneumatic Controller Emissions from a Sample of 172 Production Facilities*, November 2014.
- The Prasino Group, *Final Report- For Determining Bleed Rates for Pneumatic Devices in British Columbia*, December 18, 2013.
- The Independent Petroleum Association of Mountain States (IPAMS) and Western Regional Air Partnership (WRAP), 2006.
- Central States Air Resources Agencies (CenSARA), 2011.

In the April 2015 memo, EPA noted that the Allen et al. 2014 study (a.k.a UT/EDF Phase 2 Study) did not differentiate between controller types. However, supplemental information for the Allen et al. 2014 study does provide classification of pneumatic controllers by Subpart W types, for a subset of controllers and also determined classification based on gas flow time-series measured during the study for all measured controllers (refer to Table S4-2 from the Allen et al. 2014 study[10]). EPA could examine this information for updating emission factors for intermittent-bleed controllers. However, it may be more difficult to analyze the data for high-bleed versus low-bleed controllers since malfunctioning low-bleed controllers could exhibit characteristics of high-bleed controllers. It is our understanding that the Allen et al. 2014 study also collected meta-data for each controller that includes the manufacturer and model number of each controller and that this information is available upon agreeing to confidentiality provisions.

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[9] Shires, T.; "Onshore Oil and Gas Production – Pneumatic Controllers", Presented at the Stakeholder Workshop on EPA GHG Data on Petroleum and Natural Gas Systems, November 19, 2015.

[10] Allen, D.T., Pacsi, A., Sullivan, D., Zavala-Araiza, D., Harrison, M., Keen, K., Fraser, M., Hill, A.D., Sawyer, R.F., and Seinfeld, J.H., *Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers Supporting Information*, Environmental Science & Technology, 10.1021, Pneumatics es5040156_si_001.pdf

The manufacturer and model number would enable classification of each controller into the appropriate EPA "bucket" on the basis of the controller design rather than the measured emission profile.

Generally, the Allen et al. 2014 data showed lower emission rates per controller than the current emission factors in the GHGI. For example, the current GHGI emission factor for gas wells is 15.4 scf/hr/controller. On average, the estimate from the Allen et al. 2014 study was 5.5 scf/hr/controller, even accounting for emissions from malfunctioning controllers or related systems (i.e. a pinhole leak in the control valve) that were included in the emission factor for pneumatic controllers. There are reasons to believe that the current GHGI emission factor over-estimates the emissions from current controllers in operations. For example, many operators have changed out or retrofitted continuous high-bleed controllers as part of voluntary and regulatory programs.

The Oklahoma Independent Petroleum Association (OIPA) conducted an analysis of the Allen et al. 2014 pneumatic data to complement the data from the OIPA study, by including emissions from leaking or malfunctioning intermittent-bleed controllers. In the Allen et al. 2014 study, 10 of 320 intermittent-bleed controllers (3%) were "high emitters;" (i.e., were either leaking or malfunctioning and had an average "malfunctioning" emissions factor of 50 scf/hr). The OIPA study calculated an emission factor for vented emissions from intermittent-bleed pneumatic controllers of 0.4 scf/hr based on physical observations of actuation frequency and calculated volume of gas released per actuation. The distinction is that "vented" emissions from pneumatic controllers represent the gas released due to normal operation of the controller, while "malfunction" emissions from pneumatic controllers represent leaking or malfunctioning controllers. Applying the OIPA "vented" emissions factor of 0.4 scf/hr to 310 of the properly functioning intermittent-bleed controllers in the Allen et al. 2014 study, while applying the "malfunction" emissions factor of 50 scf/hr to the 10 leaking or malfunctioning intermittent-bleed controllers gives a weighted average emissions factor of 2.0 scf/hr for all intermittent-bleed controllers ($[(310 \text{ x } 0.40 \text{ scf/hr}) + (10 \text{ x } 50 \text{ scf/hr})]/320_{\text{controllers}} = 2.0 \text{ scf/hr}$). The OIPA study also provides information on the count of pneumatic controllers for new well sites and old well sites (including stripper wells and smaller conventional well pads). As shown in the OIPA study, a robust emission estimate must include understanding the characteristics of both of these types of wells.

Regarding the Prasino study, API cautions EPA in using data from that study as the focus was only on pneumatic controllers with manufacturer bleed rates > 6 scfh and thus the Prasino study is intentionally biased toward high emitting pneumatic controllers.

Overall, while all these recent studies present the most current data available, they likely should not be EPA's primary source of data due the variability from study to study. Addressing the use of new measurement data to update the GHGI would benefit from further evaluation of all available data by a multi-stakeholder working group. Such an approach would provide for a structured update of the applicable emission factors to complement the revised counts being obtained from Subpart W. If the EPA decides to update the inventory without such a stakeholder engagement, API recommends the use of the Allen et al. 2014 study emission factors for pneumatic controllers, as the best available current data set, which can also provide improved understanding of these emissions. As an area with expected future studies, EPA should consider that understanding of emission rates from this source is likely to evolve in the near term as new data sets and measurement techniques are considered. API is interested in maintaining an on-going dialogue of emission sources in this sector.

- ✓ (Question #3 from EPA's Production memo) The EPA seeks feedback on how to take into account reported emissions data under Subpart W for major equipment fugitives in the GHGI. For reporters using equipment leak methodology 1 (98% of reporters in RY2014), emissions data are reported at the facility level based on use of component-level EFs specified in the rule, not at the equipment level. The EPA seeks feedback on how to use such data in developing equipment-specific fugitive EFs that could be applied in the natural gas and petroleum systems sectors of the GHGI. The Subpart W specified EF for reporting vented emissions from CIPs uses the same basis (GRI/EPA) as the current GHGI. The EPA is considering adjusting the GHGI emission factor for CIP using Subpart W reported data, which takes into account operating hours.

API Comment: Existing GHGRP data on fugitive emissions reported for the production sector is of limited value for the GHGI since it relies on a set of average emission factors per component counts as prescribed by EPA and does not contain measurement information that may be useful to update the emission factors. Equipment counts reported through Subpart W could be useful for updating activity data for the GHGI, but such extrapolations would be technically challenging as discussed in Question #1. As a result, API strongly encourages a detailed stakeholder process related to determining the best method for this extrapolation given the different populations of wells expected to be covered and not covered under the GHGRP. However, EPA should refrain from using the default component level emission factors specified for Subpart W to develop equipment-based fugitive emission factors for the GHGI.

Subpart W provides counts of chemical injection pumps (CIPs) and operating hours that can be used to scale up GHGRP data to a national emission estimate. However, Subpart W does not provide information to support updating the emission factor for CIPs. The Allen et al. 2013 study (a.k.a. UT/EDF Phase 1 study) provides measurement data for 62 CIPs with an average emission rate of 0.192 scf CH_4/min/device. EPA should consider evaluating this information for updating both the default emission factor available in Subpart W and the emission factor currently used in the GHGI.

Calculations Using Subpart W Data

- ✓ (Question #4 from EPA's Production memo) The EPA seeks feedback on the methodology for allocating Subpart W data between the natural gas and petroleum production sectors. Are other approaches available for allocating Subpart W equipment and pneumatic controller counts between production types? For example, one limitation in the current methodology is that for facilities covering both oil and gas sub-basins and having separators, the count of separators-per-gas well is equivalent to separators-per-oil well.

API Comment: Following IPCC guidance, EPA separately reports production operations for Natural Gas Systems and Petroleum Systems in production operations[11], while oil and gas production activities are combined in the GHGRP. EPA's current approach of separating GHGRP data based on the ratio of oil production basins to high permeability gas, shale gas, coal seam, or other tight reservoir rock, although somewhat arbitrary is reasonable.

To aid in comparing the GHGI to GHGRP data, API suggests that EPA resolve differences in emission source types between the two reporting programs and between natural gas and petroleum production activities. For example:

- Production operators report emissions from associated gas venting and flaring in the GHGRP, but this source is not included in the GHGI;
- Well drilling emissions are a vented source in the GHGI under Natural Gas Systems, but combustion and fugitive emissions from well drilling are tracked under Petroleum Systems;
- "Wellheads" are an equipment category for reporting fugitive emissions in the GHGRP, but the GHGI reports emissions for associated gas wells, non-associated gas wells (less wells with hydraulic fracturing), gas wells with hydraulic fracturing, oil wellheads (heavy crude) and oil wellheads (light crude).

These are just a few examples where inconsistencies in terminology complicate comparing emissions between the GHGRP and Natural Gas Systems and Petroleum Systems in the GHGI.

✓ (Question #5 from EPA's Production memo) The EPA seeks feedback on whether and how to use Subpart W data to reflect geographic variation of activity factors and/or emission factors. In the current GHGI, emissions from natural gas systems are calculated separately for six NEMS regions, and emissions from petroleum systems do not have geographic variation. The update under consideration is applied at the national level. The EPA plans to explore options to reflect geographic variation in future GHGIs.

API Comment: In the Natural Gas Systems production sector, EPA reports emission factors and activity factors by National Energy Modeling System (NEMS) regions. Except for fugitive emission factors, emission factors vary from year to year due only to slight changes in the methane composition between each NEMS oil and gas supply region. The methane compositions are derived from a 2001 GTI study[12] and adjusted year to year using gross production for NEMS oil and gas supply modelled regions from the EIA.

Distinctions made between eastern and western fugitive emission factors, derived from the 1996 GRI/EPA study were based on operational differences and the extent of production of sour crude, and are no longer relevant to operations today.

API recommends that EPA drop the breakout of natural gas production data by NEMS region. This breakout gives a false sense of data accuracy, as most of the emission factor variability is based on methane concentration and not on different operating practices. In addition, regional

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[11] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 1, Section 8.0 *Reporting Guidance and Tables*, Table 8.2

[12] GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

data is not needed for the GHGI, as evidenced by the other natural gas and petroleum sectors that are only reported at the national level.

- ✓ (Question #6 from EPA's Production memo) The EPA seeks stakeholder feedback on year-to-year trends in reported Subpart W data, and whether it is more appropriate to recalculate activity factors and/or emission factors separately for each RY, or to use another approach (e.g., combine data from multiple early RYs such as the current methodology for hydraulically fractured gas well completions which uses combined RY2011 through RY2013 data to calculate the emission factor).

API Comment: For Subpart W, the 2011 and 2012 GHGRP data include estimates due to the use of BAMM, and for pneumatic controllers due to the option to estimate counts initially. In addition, data tend to improve over time as reporters become more familiar with the requirements and establish more robust reporting processes. API does recognize the value in using Subpart W data to reflect year to year trends. However, API suggests that early-year reporting data may not be as accurate as data reported in the third year and beyond. For production operations, API recommends that EPA use an average of 2013 and 2014 GHGRP data to update activity factors. As data become available for the Gathering and Boosting sector, EPA should recognize that reporting year 2016 will include the use of BAMM and even reporting year 2017 may reflect the learning curve in establishing reporting programs for this new sector.

- ✓ (Question #7 from EPA's Production memo) The EPA seeks feedback on how to address time series consistency in using AFs derived from Subpart W data—i.e., calculating activity in years between the early 1990s base year and recent Subpart W-era years. As discussed under "Time Series Considerations" the EPA might use the count of active production wells as an activity data driver for major equipment and total pneumatic controller counts in natural gas systems, and simple linear interpolation for petroleum systems. The EPA could consider taking into account other factors (e.g., year to year production changes). The EPA seeks stakeholder feedback on other factors that impact equipment counts and potential methods to incorporate these factors into the GHGI calculations.

API Comment: API examined the DrillingInfo (DI) Desktop data over the 1990-2014 period to determine if there are any unusual peaks or valleys in oil or gas well counts or production data. The trends for well counts and production data are generally the same, with no apparent outliers. Therefore, it seems reasonable for EPA to use national well count and production data to estimate emissions over the inventory time series.

However, API notes that obtaining accurate and replicable well counts is a complex issue. API is engaged in ongoing discussions with EPA about how to estimate well counts using the DrillingInfo (DI) database. At a primary level, these discussions revolve around differences in how the EPA accesses the DI data versus how API accesses the data. While EPA starts with actual raw data files, API accesses the data through a desktop application of the data that only allows for certain search parameters. This means that there are significant differences in how users can access and search the data, which makes it very difficult to replicate well counts. For example, because EPA has access to all raw well data, they are able to easily classify wells as either "oil" or "gas" based on a GOR that they calculate. Through the desktop application however, wells are classified as "oil" or "gas" based on state definitions that are not consistent across all wells. The following table illustrates the differences in well counts accessed by API through the DI database, compared to well counts reported by EPA for 2013 in the previous GHGI[13]

DI Database Well Counts for 2013 (accessed by API)		EPA Reported 2013 GHGI Well Counts[13*]	
Gas Wells	417,277	Non-associated gas wells	207,279
		Gas wells with hydraulic fracturing	244,017
Gas and Oil Wells	70,679	Associated gas wells	477,023
Oil Wells	455,243	Heavy crude oil wells	38,682
		Light crude oil wells	510,005
TOTAL	**943,199**	**TOTAL**	**1,477,006**

* Including 315,000 crude oil stripper wells (<15 Bbls per day); Reference 13 Table A-126

Unless one downloads all of the well data, which is not a feasible solution, the desktop application does not allow a user to calculate a GOR and use it as a search parameter. API urges EPA to be transparent in describing how EPA utilizes information in Drilling Info for the GHGI in order to facilitate comparisons and ensure that there is no undercounting or overcounting of wells.

We would also like to point out that the noted discrepancies in the well counts are not a new issue. For example, the U.S. Energy Information Administration (EIA) reports 514,637 producing gas wells for 2011 (as compared to 604,681 in the GHGI published in 2013) and 536,000 producing oil wells (as compared to 220,787 crude oil wells and 315,213 crude oil stripper wells in the GHGI published in 2013). For 2013, the EIA reports 484,994 producing gas wells (with gas-oil ratio > 6000 scf/barrel) but does not furnish equivalent information for oil wells.

The well counts provided in EPA's Production sector memo equal 1,315,196 (Table 4: 2013 wellheads for petroleum & natural gas combined). This value is different from the sum one derives (per table above) from the respective petroleum and natural gas tables in Annex 3 of the 2013 GHGI. Since EPA is proposing to use the number of wellheads (well count) as the normalization factor for scaling Subpart W data, it is imperative that the well count be accurate.

API is providing all of these examples to highlight the discrepancies in the data used to update the emissions estimates for the production sector and the need to have them reconciled by a transparent and structured process via a multi-stakeholders group, as previously stated.

Other Emission Sources

- ✓ (Question #8 from EPA's Production memo) The EPA discusses potential revisions to the GHGI production sector structure in a companion memo titled "GHGI of U.S. Greenhouse Gas Emissions and Sinks: Revisions under Consideration for Natural Gas Gathering and

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[13] U.S. EPA, 2015, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013", EPA 430-R-15-004, April 15, 2015; Tables A-126 and A-133.

Boosting Emissions" (February 2016). Potential revisions would include updating some of the production emission calculation methodologies based on Marchese et al. (2015) measurement data for centralized production and gathering-only facilities. With such revisions, certain emission sources would overlap with the Marchese et al. facility-level EF if current methodology were retained: dehydrator vents, Kinray pumps, and storage tanks. The EPA seeks feedback on how to improve GHGI activity, emissions, and controls data for sources located at non-gathering production sites based on available Subpart W data.

API Comment: EPA's memo on proposed revisions to the GHGI for Gathering and Boosting focuses entirely on utilizing information from the Mitchell et al. and Marchese et al. studies. However, the Mitchell et al. measurements are limited in their use because only downwind, site-level short-duration "snapshot" measurements were conducted. This approach does not provide sufficient information to properly characterize emissions at individual sites in gathering and boosting operations, much less individual sources within the sites.

API recommends that EPA postpone major updates to the GHGI for gathering and boosting emissions until GHGRP data are available. The GHGRP will provide additional activity data for gathering operations and will enable EPA to properly characterize equipment populations and distinguish between production and gathering. When this new information and characterization become available, API recommends that EPA revise the GHGI to present, separately, gathering emission estimates from production emission estimates, even if they ultimately have to be combined for reporting under the IPCC categories. This will align the inventory with the GHGRP, provide greater transparency, and enable trends to be evaluated. As stated above, API requests that EPA delay making any significant changes to the methodology until GHGRP data are available in 2017. At that time, EPA will have facility specific data for a significant number of Gathering and Boosting facilities in the country, including population information, activity data, and actual emission data for some sources.

✓ (Question #9 from EPA's Production memo) The EPA seeks stakeholder feedback on production sector sources not discussed in this memorandum.

a. For sources where GHGRP data are currently available, the EPA seeks stakeholder feedback on how GHGRP data may be used to revise current GHGI methodologies. For example, the EPA seeks stakeholder feedback on whether similar methods to those discussed in this memorandum could be used to scale up subpart W activity data for sources such as liquids unloading and hydraulically fractured (HF) gas well completions
b. For sources where GHGRP data are not currently available, the EPA seeks stakeholder feedback on data sources available for updates to those methodologies. The EPA is considering including emissions from hydraulically fractured oil well completions and workovers in the GHGI, using information from the 2015 NSPS OOOOa proposal. In addition, the EPA seeks stakeholder feedback on any currently available or upcoming activity and/or emissions data on abandoned wells.

API Comment: (a) For emission sources with data available through the GHGRP, API recommends that EPA make use of GHGRP information to update the national inventory. As mentioned in our responses above, the exception to this is where the GHGRP does not collect new emissions data but utilizes default emission factors, such as for fugitive emissions in production, pneumatic controllers, pneumatic pumps, compressors in production, and small dehydrators.

API previously commented on the use of GHGRP data for gas well completions and workovers to update emission estimates in the GHGI.[14] EPA incorporated updated emission factors for these sources, although API continues to believe that the emissions data can be well represented by only two emission factors (completions and workovers vented without REC, and all other completions and workovers) rather than the four categories used by EPA. These two categories maximize the use of GHGRP data, will be more straightforward to back cast for previous reporting years in the GHGI, and are consistent with current practices.

API cautions EPA against using the ratio of well completions and workovers to overall well counts in the GHGRP, in order to scale up completion and workover counts to the national level. Completions, by definition, only apply to new wells, although not all new wells are hydraulically fractured. Information on new wells should be available through EIA or DI Desktop. Determining an appropriate method of scaling GHGRP data may be best achieved through discussions and consideration by the multi-stakeholder group suggested by API.

(b) Although not currently required under the GHGRP, some companies have reported emissions data for oil well completions and workovers with hydraulic fracturing. API commented previously on the use of GHGRP data to derive emission factors for the GHGI.[14] API previously identified 149 reported data sets, providing emissions data for 1675 completions and 226 workovers for the years 2011 through 2013 combined (we have not examined the 2014 GHGRP data to update this analysis). API believes the GHGRP provides sufficient data to include these emissions in the GHGI, and that much more information will be available in the next few years to update the national emission estimates.

The DI database provides activity data for abandoned wells. A 2014 study (Kang et al.[15]) provides information on emissions from abandoned wells in the Appalachia region. However, many of these wells are very old, predate any abandonment criteria, were not properly abandoned and were limited to a single geographic region. Therefore, while the study did provide new information, the findings should not be considered as representative nor used as the basis for national extrapolation. A proper data set is needed that reflects geographical variability and well-age to represent emissions from abandoned wells on a national basis.

- ✓ (Question #10 from EPA's Production memo) Recent production sector studies have detected the presence of super emitters in the production sector. The EPA seeks stakeholder feedback on how to incorporate information on super emitters into estimates for the production sector. The EPA also seeks stakeholder feedback on which GHGI sources are more likely than others to act as super emitters and whether and how to apply a super emitter factor or other methodology to those sources.

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[14] Letter to Leif Hockstad and Melissa Weitz, API Expert Review Comments on EPA's Draft U.S. GHG Inventory: 1990-2013, January 9, 2015.

[15] Kang et al. (2014) "Direct Measurements of Methane Emissions from Abandoned Oil and Gas Wells in Pennsylvania". Proceedings of the National Academy of Sciences of the United States of America. Available at: http://www.pnas.org/content/111/51/18173.full.pdf]

API Comment: Recent measurement studies have shown skewed "long tail" distributions for source-level measurements, where a few emission sources may contribute a disproportionately high fraction of emissions. This is a common and expected statistical distribution for random events, such as fugitive emissions from process components and equipment malfunctions. A combination of variability in production and non-steady state emissions may result in a 'fat-tail' distribution even in the absence of operational upsets. Emission factors derived from such measurements already account for the emission distributions throughout the range of observations for each of the sources, including the emissions at the high range of the tail.

The approach raised by EPA, of potentially, separately adjusting the national inventory for the so called 'super emitters,' is not appropriate. API contends that there should not be *any consideration* of using downwind offsite measurements – especially those that depend on short duration, snapshot measurements – to characterize emissions in the GHGI. Recent studies in the Barnett Shale region indicate that there might be several order of magnitude differences in repeated emissions from a given set of sites, probably due to stochastic variables that are transient in nature. In particular, a study of 22 separate flights around the same compressor station[16] indicated that facility-level emissions ranged from 0.3 to 73 g CH_4/sec with highly skewed distributions (mean=14 g/sec and median = 7.4 g/sec). Again, API suggests that the EPA inventory team consult with the EPA ORD's Eben Thoma regarding the adequacy of downwind ambient concentration measurements in determining emissions.

All the studies aiming to quantify fugitive emissions indicate that the distribution of emissions and the shape of its tail are not well understood. API insists that both EPA and the scientific community do not have enough information to identify the reasons for the variability of some emission sources. All measurements have some degree of uncertainty. This is especially true for short duration snapshot measurements conducted offsite, which fail to differentiate between routine episodes of high emissions, operating conditions, or operators errors that may lead to periodic higher emissions. For example, one study[17] focused on "super-emitter" quantification in the Barnett Shale and relied on measurements of 1-5 minutes in duration at distances of up to several kilometers downwind in a region with high oil and gas site density.

EPA's ORD research[5] that was conducted with strict data quality control parameters, longer sampling times, and nearer pad sampling, indicated that, at best, downwind measurements provide screening level accuracy with ±60%. Insufficient research exists to validate high downwind measurements with on-pad emission sources such that it could be used to characterize national emission estimates for a program like the GHGI. API concurs with EPA's ORD that in order to properly quantify emissions measurements, they should be taken over a long period of time in order to capture the full range of variability, rather than rely on just peak emissions. Assuming that peak emissions occur all the time would lead to biased results.

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[16] Nathan, B.J., Golston, L. M., O'Brien, A.S., Ross, K. Harrison, W. A., Tao, L., Lary, D. J., Johnson, D. R., Covington, A. N., Clark, N. N., and Zondlo, M. A., *Near-field characterization of methane emission variability from a compressor station using a model aircraft.* Environmental Science & Technology, **49,** 7896–7903 2015

[17] Yacovitch, T. I., Herndon, S.C., Pétron, G., Kofler, J., Lyon, D., Zahniser, M. S. and Kolbacovitch, C. E. et al. *Mobile laboratory observations of methane emissions in the Barnett Shale region.* Environmental Science and Technology. **49**, 7889–7895, 2015

In summary, API maintains that adjusting emissions for what EPA terms ’super emitters’ may lead to gross overestimation due to the unpredictable nature of such high emissions events and may also lead to duplicative counting, since these events are already part of the emission distribution that is used to derive emission factors. For example, if a connection failure is posited as the cause of a theoretical site being deemed as a theoretical “super-emitter”, emission factors developed from in-field measurements of a population of connectors already account for some of these components emitting at a high rate. Consequently, API insists that since EPA does not have sufficient information to characterize and understand this then no such adjustment to the GHGI inventory approach should be considered.

Responses to EPA Questions for Revisions under Consideration for Gathering and Boosting Emissions

Data Availability

- ✓ (Question #1 from EPA’s Gathering and Boosting memo) The EPA is seeking stakeholder feedback on additional data available to consider in revising G&B emission estimates at this time. The EPA seeks stakeholder feedback on the proposed approach to use Marchese et al. estimates for national activity data. Are additional data sources or approaches available to estimate national G&B activity?

API Comment: The Marchese et al. study results are based on facility level, downwind short-duration “snapshot” measurements conducted during the Mitchell et al. study. Marchese et al. used that data to model the total methane emissions from approximately 120 facilities. The modeled results are then “scaled” – using multiple assumptions - to a national level to represent the methane emissions from over 4,500 Gathering and Boosting facilities.

As indicated in our general comments, API urges EPA to wait on any significant revisions to the GHGI related to Gathering and Boosting until the GHGRP data are available. Significant activity data will be reported through the GHGRP, including throughput volumes and equipment counts. This information will be superior to the Marchese et al. study for developing national Gathering and Boosting activity data.

- ✓ (Question #2 from EPA’s Gathering and Boosting memo) Replacing current GHGI EFs for large reciprocating compressors and stations with the EF based on Marchese et al. G&B station emissions may introduce double counting of the “mixed category” sources based on current GHGI methodology. The EPA’s updates under consideration for the G&B sector (this memorandum) and production sector (Inventory of U.S. Greenhouse Gas Emissions and Sinks: Revisions under Consideration for Natural Gas Production Emissions (February 2016)) in combination avoid potential double counting issues by calculating emissions for each as distinct sectors. Please comment on the overall approach under consideration for production and G&B.

API Comment: The Mitchell et al. study relies on offsite, downwind measurements, using inverse flux methodology to derive emissions over short durations. These types of measurements have significant uncertainty, which has been documented by EPA’s ORD[5]. EPA’s proposed approach to segregate Gathering and Boosting emissions from Production is specifically designed to utilize data from the Marchese et al. study[4], which is a desktop modeling study based on the Mitchell et al. measurements[3] but is inconsistent with the Mitchell et al study. API does not support the use of the emissions data from the Mitchell et al. or Marchese et al. studies for updating the GHGI.

The API further cautions the EPA on the development of new national emissions factors based on the Mitchell et al. study due to the large degree of variability and small sample size for the study. For the 114 facilities, emission rates ranged more than 4 orders of magnitude (from 0.6 to 600 scf CH_4/minute). Part of this variability is inherent in the short sample durations for the plumes in the study (30-120 seconds). Given the wide variation in facility emission rates from a study of 22 separate flights around the same compressor station[16], which indicated that facility level emissions ranged from 0.3 to 73 g CH_4/sec with highly skewed distributions (mean=14 g/sec and median = 7.4 g/sec), more context is needed for understanding emission rates in the Mitchell et al. study before considering application to national emission estimates.

In attempting to avoid double counting of emissions sources, EPA is artificially defining Production versus Gathering and Boosting equipment. For example, EPA is proposing to assign emissions from all pneumatic controllers, chemical injection pumps, dehydrator vents, and Kimray pumps to the Production sector. This will give the false impression that these sources only occur in Production.

API recommends that EPA wait until data are available through the GHGRP for the Gathering and Boosting sector. We believe this information will better represent the emission sources associated with Gathering and Boosting (recognizing that some Gathering and Boosting operations will continue to be reported under the Production sector due to the location of a well at the Gathering/Boosting site). In addition, we recommend that EPA report emissions from Gathering and Boosting separate from the Production sector, or as a subset of the Production sector. This will provide greater transparency and comparison to the GHGRP than combining Gathering as part of the Production sector, as is currently reported in the GHGI.

- ✓ (Question #3 from EPA’s Gathering and Boosting memo) As discussed in this memorandum, G&B data will be available in 2017 through GHGRP. GHGRP data could allow the EPA to calculate emissions for individual equipment types as opposed to using emission factors and activity data at the station level. The EPA seeks stakeholder feedback on the two approaches. The EPA could considering using the station level approach for the 2016 GHGI, and then re-evaluating and potentially revising the approach with new GHGRP data in the 2017 GHGI, or could consider implementing updates to the G&B sector starting with the 2017 GHGI and using GHGRP and/or the Marchese et al. data at that time.

API Comment: API does not believe the Marchese et al. study results are appropriate for updating the national inventory and encourages EPA to wait until the Gathering and Boosting data are available through the GHGRP. As EPA indicates, the GHGRP data will allow the EPA to calculate emissions for individual emission source types as opposed to using emission factors and activity data at the station-level. Data for individual equipment types will be significantly more useful and transparent than emission factors and activity data at the station level. There is no need to introduce a significant revision to the GHGI now to accommodate the Marchese study information, only to later have to significantly revise the methodologies again to utilize the GHGRP data.

- ✓ (Question #4 from EPA's Gathering and Boosting memo) The EPA seeks feedback on whether and how to use the Marchese et al. data to reflect geographic variation of activity factors and/or emission factors. In the current GHGI, emissions from G&B sources are calculated separately for six NEMS regions along with production sources. The update under consideration would be applied at the national level. The EPA plans to explore options to reflect geographic variation in future GHG inventories.

API Comment: The small population size of the underlying Mitchell et al. study, the lack of emission source detail, and the numerous compounding assumptions made in the Marchese et al. study to extrapolate the modeled results do not provide sufficient certainty to use the study results to characterize the Gathering and Boosting Sector. Nor does the Marchese study provide sufficient information to characterize geographic variability. As mentioned above, in response to questions raised in the Production memo, API recommends that EPA discontinue breaking out natural gas production data by NEMS region and instead report Production sector emissions data at the national level only, as EPA does for the other sectors under Natural Gas Systems and Petroleum Systems. Similarly EPA should not attempt to calculate emissions from the Gathering and Boosting sector for individual NEMS regions.

Time Series Considerations

- ✓ (Question #5 from EPA's Gathering and Boosting memo) The EPA seeks feedback on the appropriateness of using the Marchese et al. based G&B station EF across all years of the time series, or whether there are approaches that may be considered for reflecting changing industry trends impacting emissions over time.

API Comment: The Marchese et al. study, which is based primarily on drive-by, snap-shot measurements from the Mitchell et al. study, does not provide useful data for characterizing current national emissions, nor does it provide sufficient information to reflect emission trends over time.

- ✓ (Question #6 from EPA's Gathering and Boosting memo) The EPA seeks stakeholder feedback on the activity driver (volume of marketed onshore gas production) under consideration. Other options for the activity driver could include well count data or other gas production categories. Please comment on which activity driver would be the most appropriate to show trends in G&B.

API Comment: EPA will have significant activity data reported for the Gathering and Boosting sector through the GHGRP starting in 2017. API recommends that EPA evaluate this information when it's available to identify activity drivers for scaling Gathering and Boosting emissions data to a national level. API also points out that it may take more than one reporting cycle to work through data quality concerns associated with the first year of reporting for a new sector.

- ✓ (Question #7 from EPA's Gathering and Boosting memo) The EPA seeks stakeholder feedback on trends in G&B activity data that would result in more or fewer stations per volume of marketed onshore gas production during any point in the GHGI time series. The EPA requests stakeholder feedback on how upcoming subpart W G&B activity data (available in 2017) could be used to inform the time series activity data to reflect ongoing trends.

API Comment: As noted in our comment to question #6, API expects the activity data reported through the GHGRP for the Gathering and Boosting sector to provide significant information for developing national scaling factors and similarly will be appropriate data for informing activity data over the time series.

- ✓ (Question #8 from EPA's Gathering and Boosting memo) Since the EIA does not publish separate values for the onshore portion of marketed natural gas production prior to 1992, the EPA is considering using the relationship of onshore marketed production to onshore gross withdrawals in 1992 to estimate marketed onshore production in 1990 and 1991, based upon onshore gross withdrawals for these two years. Are there alternatives to addressing this missing AD?

API Comment: API supports EPA's proposal to relate onshore marketed production to onshore gross withdrawals in 1992 in order to estimate marketed onshore production in 1990 and 1991.

- ✓ (Question #9 from EPA's Gathering and Boosting memo) Although it is not possible to directly compare the G&B emissions estimate developed with GRI/EPA study data to the Marchese et al. results, it is evident that the G&B emissions from Marchese et al. are significantly higher than estimates in the current GHGI. The EPA seeks stakeholder comment on this discrepancy.

API Comment: It is not appropriate to compare the Marchese et al. modeling information which is based on short-duration, off-site ambient concentration measurements, which rely on inverse flux methods to derive emissions; to source specific emission estimates. The site level measurements conducted in the Mitchell et al. study significantly limit the use of the data for updating the national inventory, which is compiled from source level emission estimates. API urges EPA to delay revising the emission estimation methods for the Gathering and Boosting sector until more data is available for this sector through the GHGRP.

Gas Processing

- ✓ Marchese et al. also measured the methane emissions from 16 natural gas processing plants using a similar approach as described above for G&B stations. The results of the Marchese et al. testing were scaled to the estimated 600 national gas processing plants using a similar Monte Carlo simulation as was used for G&B stations. The results of the Marchese et al. simulation was a national methane emission estimate for gas processing plants of 506 Gg. As with the G&B stations, Marchese et al. estimated that the emission results were biased low for several factors. The brief sampling period did not capture routine maintenance and upset emissions. In addition the sampling method did not capture a significant portion of the compressor exhaust emissions. Marchese et al. compared their findings to the EPA GHGI of 2012 emissions. The net GHGI methane emissions for 2012 from processing plants were 891 Gg. The net GHGI emissions from processing plants, excluding compressor exhaust and blowdown/venting emissions were estimated to be 666 Gg. EPA seeks stakeholder comment on the potential use of Marchese et al. results for the processing sector.

API Comment: As mentioned previously, measurement data from the Mitchell et al. study are not particularly useful for updating the GHGI because the data lack emission source detail. Substantial new activity data and some measurement data are available for gas processing facilities that report through Subpart W. EPA now has four years of fugitive emission surveys and measurement data for specific emission sources and activity data that can be used to update the GHGI. API encourages EPA to make use of the survey results and actual measurements reported in GHGRP. In the November 2015 stakeholders' workshop, API presented a preliminary comparative analysis of methane emissions from equipment leaks from natural gas processing, showing that it is about six times larger in the GHGI as compared with the GHGRP. Although the number of gas plants reporting to the GHGRP is different than the number of gas plants in the GHGI, this difference cannot fully account for the emission differences. API would welcome further collaboration with EPA to address these differences and develop a procedure that incorporates the GHGRP measurement data in the GHGI.

API's comments above are based on our long term engagement in reviewing and providing information for the U.S. GHG Inventory. It includes observations and recommendations for careful QA/QC of data extracted from the mandatory GHGRP to improve the validity and representativeness of data used for the U.S. GHG Inventory. API recognizes that emerging data from recent field studies have raised concerns about measurements uncertainty, and recognizes the need for a thorough discussion of means of improving the methodology to ensure collection of robust measurement data. We reiterate our recommendation for EPA to form a multi-stakeholder workgroup to discuss updating the national GHGI to incorporate information from recent measurement study results and Subpart W data.

API appreciates the opportunity to provide comments on the proposed revisions to the U.S. national GHG Inventory and EPA's willingness to work with industry to improve the data used for the national inventory. API encourages EPA to continue these collaborative discussions and is available to work with EPA to make best use of the information available under the GHGRP to improve the national emission inventory. We look forward to continuing our collaborative work in the GHGI development process.

Sincerely,

Karin Ritter

cc: Alexis McKittrick, Climate Change Division

Appendix D

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Article
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Assessment of Methane Emissions from Oil and Gas Production Pads using Mobile Measurements

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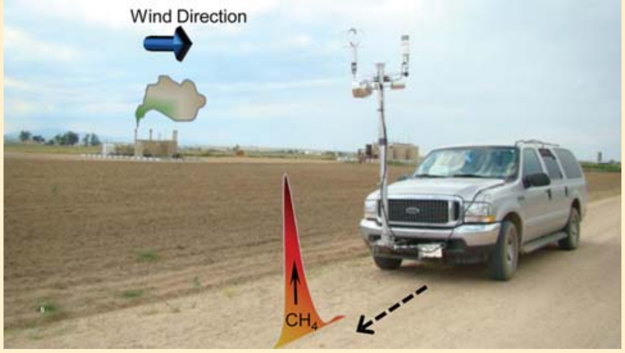
Supporting Information

ABSTRACT: A new mobile methane emissions inspection approach, Other Test Method (OTM) 33A, was used to quantify short-term emission rates from 210 oil and gas production pads during eight two-week field studies in Texas, Colorado, and Wyoming from 2010 to 2013. Emission rates were log-normally distributed with geometric means and 95% confidence intervals (CIs) of 0.33 (0.23, 0.48), 0.14 (0.11, 0.19), and 0.59 (0.47, 0.74) g/s in the Barnett, Denver-Julesburg, and Pinedale basins, respectively. This study focused on sites with emission rates above 0.01 g/s and included short-term (i.e., condensate tank flashing) and maintenance-related emissions. The results fell within the upper ranges of the distributions observed in recent onsite direct measurement studies. Considering data across all basins, a multivariate linear regression was used to assess the relationship of methane emissions to well age, gas production, and hydrocarbon liquids (oil or condensate) production. Methane emissions were positively correlated with gas production, but only approximately 10% of the variation in emission rates was explained by variation in production levels. The weak correlation between emission and production rates may indicate that maintenance-related stochastic variables and design of production and control equipment are factors determining emissions.



INTRODUCTION

Environmentally responsible development of oil and gas assets requires an understanding of atmospheric emissions of methane (CH_4) and other organic pollutants as well as their potential impact on local and regional air quality and greenhouse gas budgets. Emissions are associated with many different processes in upstream (well development and production) and midstream (transportation and storage) oil and gas activities.[1,2] Although differing in profile, emissions occur in all phases of well construction, drilling, and completion, and continue as part of the ongoing production processes.[3] Oil and gas production pads (pads) typically consist of well heads, separation units, and storage tanks. Emissions from pads can be difficult to measure and model due to temporal variability and the large number of potential sources.[4,5] Pad emission profiles depend on a variety of factors including the geological formation, equipment design and maintenance state, and on operational procedures. For example, depending on engineering and control strategies, atmospheric-pressure condensate storage tanks are a significant potential source of emissions and can be challenging to measure.[6,7] Pad emissions can also vary over time as wells age and production levels and pressures change. Improving our understanding of emissions from production sites requires a combination of approaches, including estimating emissions using engineering calculations for inventories,[2,8,9] direct measurements for refinement of emission and activity factors,[10] and new inspection techniques to inform departures from routine operations and support compliance activities.[11]

Direct (onsite) measurements can provide information on component-level emissions, but are resource intensive, requiring site access and special safety considerations. Furthermore, the high site-to-site variability decreases the probability of obtaining a representative sample from a small number of sites. To complement direct measurement approaches, a number of research groups are investigating the use of mobile inspection techniques to locate and assess emissions from off-site observing locations.[4,12−14] These emerging approaches vary with respect to execution requirements and emission estimation techniques; however, their mobile nature facilitates identification of unknown emission sources (e.g., pipeline leaks) and anomalous operating

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conditions (e.g., malfunctions). Unlike direct measurements, mobile approaches typically cannot isolate specific emitting components and are generally less precise than direct measures but are comparatively easier to implement, enabling emission assessments to be made at a greater number of locations on a more routine basis.

This paper describes a novel mobile inspection approach, EPA Other Test Method (OTM) 33A,[17] and its use to generate CH_4 emission rate data from oil and gas production sites in the Denver-Julesburg (DJ) Basin, the Barnett Shale, Pinedale, and Eagle Ford from 2010 to 2013. OTM 33A uses a combination of mobile sampling to identify sources and stationary measurements to quantify emissions. In addition to the analysis of repeated measurements at nine sites, the emission estimates from the OTM 33A field studies were compared with recent on-site studies led by the Eastern Research Group (ERG)[15] and Allen et al.[16] The ERG study,[15] conducted for the City of Fort Worth, TX, used both direct measurement and source estimation methods to characterize CH_4 and volatile organic compound emissions at 388 production sites containing wells, produced water storage tanks, separators, and compressors. Component-level source identification in the ERG study[15] was accomplished by infrared camera observations and direct source measurements were conducted using Hi Flow samplers (Bacharach Inc., New Kensington, PA), toxic vapor analyzers, and evacuated canisters. The measurements were used by the City of Fort Worth to evaluate the adequacy of setback provisions for pads and compressor stations. The results of the ERG study[15] indicated that compressors, leaking tank thief hatches, and pneumatic valve controllers are the most frequently encountered and significant emissions sources of CH_4. Using similar on-site measurement techniques, Allen et al.[16] measured CH_4 emissions from 150 production sites in four regions of the United States to evaluate engineering estimates of CH_4 emissions from natural gas production that are used in national inventories. Their results indicated that emissions from pneumatics and equipment leaks were higher than estimated in the EPA greenhouse gas (GHG) emissions inventory.[16]

■ MATERIALS AND METHODS

OTM 33A[17] is a mobile inspection approach used to locate sources and determine real-time emission rates with screening-level accuracy (±60%), without the need for site access or location-specific modeling. The technique is applicable to select oil and gas sources such as roadway proximate pads located in relatively open areas. In addition to downwind vehicle access and favorable plume transport conditions required for all mobile assessment methods, the emission characterization portion of OTM 33A relies on relatively consistent meteorological conditions, obstruction-free line of sight observation, and a knowledge of the distance to the source.[17]

Sampling Platform Design and Protocol. The OTM 33A equipment configuration, further described in OTM33A Appendix A,[17] used either a G1301-fc cavity ring-down spectrometer (Picarro, Inc., Santa Clara, CA) or a GG-24-r off-axis integrated cavity output spectrometer (Los Gatos Research Inc., Mountain View, CA) as CH_4 concentration measurement instruments (CMIs). The mobile measurement platforms were sports utility vehicles containing the CMI, computer control system, and battery systems allowing engine-off instrument operation during stationary observations to prevent self-sampling of vehicle exhaust. The vehicles were fitted with rotatable front-mounted masts with a height of 2.7 m allowing the CMI probe and meteorological instruments to be located away from the body of the vehicle. Primary wind field data were acquired using a model 81000 V Ultrasonic Anemometer (R.M. Young, Inc., Traverse City, MI). A collocated compact weather station (model AIO 102780, Climatronics Corp., Bohemia, NY) provided secondary wind data along with temperature, atmospheric pressure, and relative humidity measures. Location was recorded using a Hemisphere Crescent R100 Series GPS system (Hemisphere GPS, Calgary, AB Canada). A LabView (National Instruments, Inc., Austin TX) computer program time-aligned the data stream while allowing user control of the system.

The accuracy, linearity, and range of the CH_4 CMIs were confirmed in predeployment testing with in-field accuracy verified to be within ±5% of actual using nominal 20 ppm CH_4 (air balance) gas standard challenges as per OTM 33 Section 9.4.[17] The CMI readings were not corrected for atmospheric water vapor (OTM 33A Appendix A)[17] which introduces an approximate 1.5% average negative bias to CH_4 emission determinations for the conditions encountered in this study.

For a typical pad assessment, emissions were located through downwind, drive-by inspection, keying on sharply elevated CH_4 spikes indicative of proximate source plumes. Maximizing real-time CH_4 concentrations measured by the CMI, the vehicle was positioned in the plume at a safe and appropriate downwind observing location with the probe facing the source, and the engine was turned off. Distance from the measurement vehicle to the emission source ranged from 10 to 200 m with an average distance of 57 m. Data were acquired for a 15 to 20 min time period with the vehicle remaining stationary. Auxiliary data from infrared cameras (FLIR Systems, Inc., Boston MA), when available, helped identify the source location, facilitating laser rangefinder measurements of the distance from the mobile platform to the source. Distances were later confirmed through Google Earth images coupled with wind-concentration rose data. The vehicle was positioned to minimize line-of-sight wind flow obstructions.

Emission rate estimates were calculated using a point source Gaussian (PSG) approach with a custom MATLAB (MathWorks, Natick, MA) analysis program (OTM 33A Appendix F1).[17] This approach relies on variations in wind direction to move the plume around the observation location in three dimensions; further assumptions include a point source and Gaussian plume dispersion. The analysis software time-aligned the measurements to correct for sampling line delay, rotated the 3-D sonic anemometer data to polar coordinates centered on the predominant wind direction, and binned the CH_4 concentrations by wind direction data in ten degree increments. The results were fitted with a Gaussian function to determine the average peak CH_4 concentration in the plume. Background concentrations were determined by the program during time periods with no plume-probe overlap (OTM 33A Section 8.7).[17] The program calculated the representative atmospheric stability indicator (ASI) from an average of the turbulence intensity (TI), measured by the 3D-sonic anemometer and the standard deviation in 2-D wind direction ($\sigma\theta$), acquired by the compact meteorological station. By defining a seven unit ASI scale with steps of equal increments (TI = 0.025, $\sigma\theta = 4.0°$), an ASI value for each measurement was assigned which ranged from 1 (TI > 0.205, $\sigma\theta > 27.5°$) to 7 (TI < 0.08, $\sigma\theta < 7.5°$), roughly corresponding to the Pasquill stability classes A through D.[18] For the PSG emission estimate, the values of horizontal (σy) and vertical (σz) dispersion are determined from an interpolated version of point source dispersion tables using the measured source distance and the ASI (OTM 33A Section 12, Appendix F1).[17] The PSG emission estimate (q) is a simple 2-D Gaussian integration (no reflection term) multiplied by mean wind speed (u) and the peak concentration (c) determined by the Gaussian fit: ($q = 2\pi \cdot \sigma y \cdot \sigma z \cdot u \cdot c$).[17]

Method Validation Using Controlled Release Experiments. A set of 107 controlled CH_4 release experiments were conducted to investigate data quality indicators and the expected accuracy range for the PSG approach in relatively obstruction-free, open areas as encountered in this study (OTM 33A Section 9).[17] The experiments used single point releases from slightly dispersed, mass flow-controlled cylinders of 99.9% CH_4, performed at a variety of site locations, observation distances, and under a range of atmospheric conditions. Release rates ranged from 0.19 g/s to 1.2 g/s with 60% at approximately 0.6 g/s. Based on these experiments, a primary set of three data quality indicators was identified: (1) fitted peak CH_4 concentration centered within ±30 degrees of the source direction; (2) an average in-plume concentration greater than 0.1 ppm; and (3) a Gaussian fit with an $R^2 > 0.80$. The plume centering indicator helps ensure the identity of the upwind source and can protect against off-axis interfering sources and poor plume advection conditions. The concentration limit helps protect against insufficient plume transport and the R^2 indicator helps identify interfering sources and obstructed wind flow conditions (non-Gaussian transport).

The percent error ([estimated emission rate-release rate]/[release rate]) of the controlled release experiments that met the data quality criteria ranged from −60% to 52% with 72% of the measurements within ±30%. Without application of the data quality indicators, the set of release experiments produced accuracy values ranging from −87% to 184% of actual. The 184% overestimate was believed to be due to pooling and release under partially stagnant conditions and a trial wind variance indicator was developed for this case (not observed in field trials). Factors affecting accuracy can include insufficient plume advection and nonrepresentative concentration profiles caused by near-field obstructions or poor plume-probe overlap. Potential data quality indicators such as wind speed and plume concentration statistics are being investigated as part of OTM 33A method development.[17] For the current analysis, only measurements that met the three primary criteria were included (representing 77% of the controlled release measurements and 71% of the field measurements).

Description of Field Studies and Production Data. OTM 33A was used in eight two-week field campaigns in four oil and gas production basins: Colorado DJ Basin, July 2010 and 2011; Texas Barnett shale, September 2010 and 2011; Texas Eagle Ford Shale, September 2011; and Wyoming Pinedale, which includes the Pinedale Anticline and Jonah fields, June 2011, July 2012, and June 2013. Data sets for each individual basin were combined as the methods of data collection were similar, although there were some software and hardware improvements in later studies. All measurements were collected in the daytime on days with no significant precipitation.

Oil and gas production information for the counties sampled was obtained from DI Desktop (Drillinginfo, Austin, TX). Included in the data set were well type, operator, first production date, spatial coordinates of the well, and annual and monthly hydrocarbon liquids, gas, and water production levels. OTM 33A measurements were spatially matched with production data using aerial imagery (Google Earth[19] and ArcGIS[20] base maps). When coordinates did not align with aerial imagery, additional data sets provided by the State of TX[21] and State of CO[22] were used to cross-reference location information. Monthly production values were available for 81% of the measurements. When monthly production was not available, annual values were converted to monthly estimates. The matched data set was analyzed using R[23] and ArcGIS 10.[20]

Both emissions estimates and production values were log-normally distributed and for this reason, data in figures are shown on a log scale. The mean and 95% CI of the log-transformed data were calculated using a nonparametric bootstrap[24,25] and then transformed back into the original scale. The nonparametric bootstrap involved resampling with replacement 1000 times, the mean of each of the samples was taken and the 95% CIs were calculated from the resulting normally distributed means. The nonparametric bootstrap was chosen because it does not assume the underlying data comes from a normal distribution. To compare OTM 33A emissions estimates with the direct measurement studies conducted by ERG[15] and Allen et al.,[16] direct measurements were converted from CH_4 scfm into g/s using a molar volume of 40.87 mol m^{-3} and summed by site. Measurements from the ERG study[15] were matched with the corresponding monthly production values from DI Desktop (Drillinginfo, Austin, TX) based on the recorded Entity ID. Production values for the sites measured by Allen et al.[16] were reported by the well operators to the study team.

RESULTS AND DISCUSSION

Description of Sites with Repeat Measurements. The OTM 33A mobile inspection approach was used to identify and assess CH_4 emissions from roadway proximate well pads with an average in-plume concentration enhancement over back ground >0.1 ppm. No attempt was made to measure or statistically account for well pads with apparently low (and thus difficult to measure) emissions. In many cases, infrared camera videos (examples in Supporting Information (SI) Supplemental B) acquired from off-site observing locations, simultaneously with the CH_4 measurements, helped to identify specific emission sources. Storage tank-related emissions were frequently observed. The emission rates and video examples presented here may not be representative of current conditions due to engineering advancements, changes in work practices, and the implementation of new state regulations.

To improve understanding of both technique and source variability, repeat measurements (three or more) were made at nine sites in the Pinedale Basin, with the number of measurements per site ranging from 3 to 21 (SI Table S1). The consistent winds and lack of obstructions in the Pinedale Basin create favorable conditions for OTM 33A. Measurements were made in different years at four of these sites (Figure 1), and the time between measurements ranged from <1 day to 732 days (SI Table S1). For sites A–G, the 95% CI for the geometric mean was less than 1 g/s while at sites H and I, large variations in emissions were observed, resulting in a CI ≥ 2 g/s (SI Table S1).

The results indicate that while relatively low emissions (<2 g/s) frequently persist over time, the larger emissions observed using OTM 33A are likely episodic in nature. One source of persistent low-level emissions observed with the infrared camera is believed to be a vented produced water tank at Site C (SI Video S1). Previous studies have shown that flashing

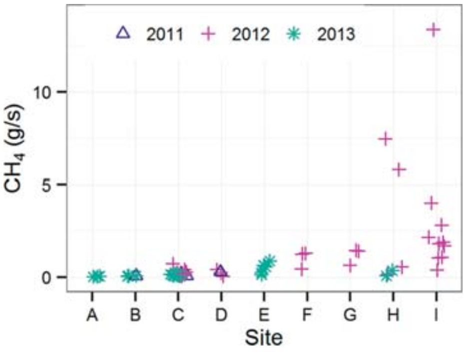

Figure 1. CH_4 emission rates (g/s) measured at repeated sites in Pinedale, WY by year.

from a condensate tank after a separator dump can result in episodic large emissions.[6] CH_4 emissions greater than 2 g/s were observed at 13% of the 210 unique sites measured. The variability of emission rates at sites H and I indicates that these larger emissions may be episodic events that cannot be used to infer annual emission rates without a greater understanding of their frequency and duration (Figure 1).

Site I was measured on four separate days in 2012. On each of the days, the emissions appeared to originate from the same tank. Infrared videos indicate that all of the emissions >3.0 g/s occurred during the time period that a thief hatch on a condensate tank was open (SI Video S4, Video S5, and Video S6). On the last day the site was measured, the thief hatch was closed and the measured emissions seemed to originate from a pressure relief device and were <3.0 g/s (SI Video S7).

Another potential cause of variation in emissions levels is the variability in plume capture. Depending on meteorological conditions, the plume measured can include all of the sources on the pad or only some of the sources (Figure 2). Measurements were made at Site H on 3 days in 2012 and 1 day in 2013 (four and two independent emission measurements, respectively). The higher emissions observed were only present on one of the days in 2012 and originated from the tank on the north side of the pad (SI Video S2), whereas the smaller emissions seemed to originate from the southern edge of the pad (SI Video S3).

Comparisons of CH_4 Emissions by Basin and with Direct Measurement Studies. A total of 318 OTM 33A measurements that met the data quality criteria were collected. Of these measurements, 31 were excluded from the analysis because the measured emissions either did not originate from routine pad operations (e.g., evidence of active pad maintenance, pipeline leaks, gas processing plants, etc.) or no current production data were available, resulting in a total of 210 unique sites. The sites were classified into gas or oil pads based on the TX Railroad Commission definition of a gas well[26] (>100 Mscf of gas per barrel of hydrocarbon liquids). Gas pads constituted 93%, 2%, 75%, and 84% of the sites measured in the Barnett, DJ, Eagle Ford, and Pinedale basins, respectively. Methane emissions were averaged by site and month, resulting in a total of 228 combinations of emission and production values. Due to the small sample size in the Eagle Ford ($n = 4$), these measurements were excluded from the basin comparison (Figure 3). CH_4 emissions were log-normally distributed with geometric means and 95% confidence intervals (CIs) of 0.33 (0.23, 0.48), 0.14 (0.11, 0.19), and 0.59 (0.47, 0.74) g/s in the Barnett, Denver-Julesburg, and Pinedale basins, respectively. Emissions by basin were compared using a Kruskal–Wallis one-way analysis of variance test and pairwise Wilcoxson rank-sum tests and were found to be significantly different ($p < 0.05$). The differences in emissions between basins are likely a result of a combination of factors, including but not limited to variations in gas and oil production, emissions control devices, and natural gas and oil composition.

The OTM 33A measurements were compared with the results of the direct measurement studies of routine pad operations conducted by ERG[15] and Allen et al.[16] (Figure 3). The studies encompass a range of pads that vary with respect to oil and gas composition, production levels, amount and type of production equipment, age, and emission control measures, resulting in a broad distribution of emissions. The mean of the CH_4 emissions measured using OTM 33A in the Barnett Shale, 0.33 (0.23, 0.48) g/s, is more than twice the mean of the emissions measured by ERG[14] 0.14 (0.11. 0.18) g/s. Nevertheless, the interquartile range of the OTM 33A measurements in the Barnett falls within the interquartile range of the ERG emissions estimates despite the differences in the measurement methods and the bias toward higher-emitting sites in the OTM 33A measurements.

Both onsite and remote measurement techniques can provide important information on emissions. Whereas direct measurements can accurately quantify component-level emissions, they are less amenable to locating and assessing malfunction-related or large short-term emissions such as condensate tank flashing. The measurements by Allen et al.[16] were limited primarily to equipment leaks, pneumatic controllers, and chemical injection pumps. Condensate tank emissions were measured at some sites but rarely could all of the emission points be accessed. In the ERG study,[15] due to

Figure 2. Map of repeated measurements at sites H and I. The directions of the colored arrows indicate mean wind directions and the locations indicate the locations of the mobile platform during the measurement.

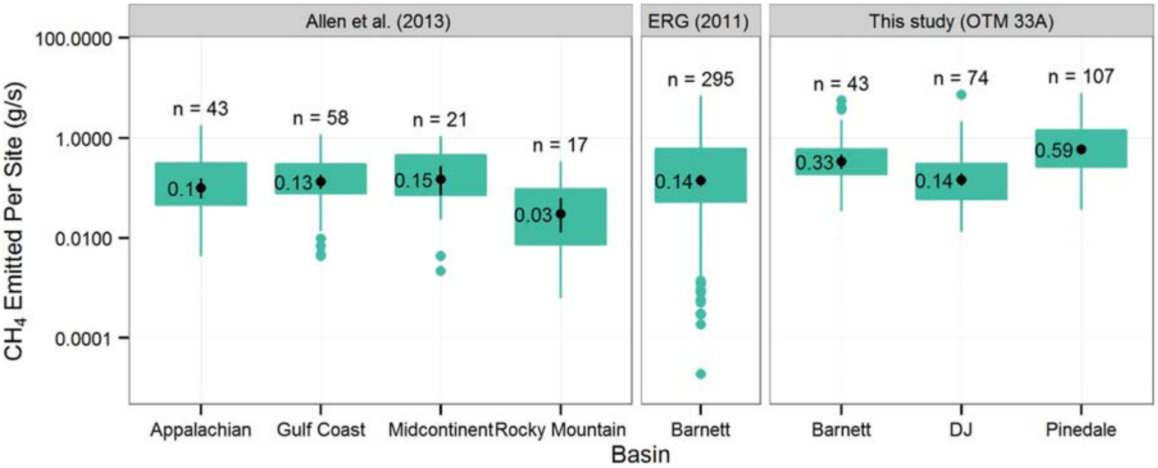

Figure 3. Comparison of measured CH_4 emissions per pad (g/s) from Allen et al.,[16] ERG,[15] and OTM 33A by basin. Boxes represent the 1st and 3rd quartiles of the data, while whiskers extend to the largest measurement that is within 1.5 times the interquartile range (IQR). Means and 95% CIs are shown in black and were calculated using a nonparametric bootstrap.

lack of condensate production, flash emissions were not represented. Although both studies measured fugitive component leaks, neither identified or measured potentially larger maintenance-related emissions (e.g., open thief hatch or failed pressure relief value). In contrast, OTM 33A measurements generally represent an integrated plume including all potential sources on a pad. Supporting infrared camera footage from the OTM 33A studies indicated that emissions often originate from condensate storage tanks which have previously been shown to comprise a significant source[6,5] (SI Supplemental B). OTM 33A is also more likely to capture malfunction-related CH_4 releases than direct measurement methods because of its mobile and off-site measurement capabilities.

However, the remote nature of the OTM 33A method and its application in these studies to only sites with downwind average in-plume concentrations greater than 0.1 ppm result in an effective lower sampling limit of approximately 0.010 g/s, compared with <0.001 g/s limits for the on-site measurement techniques (Figure 4a). As a result, the OTM 33A measurements only represent the upper end of the distribution in this comparison (Figure 4b).

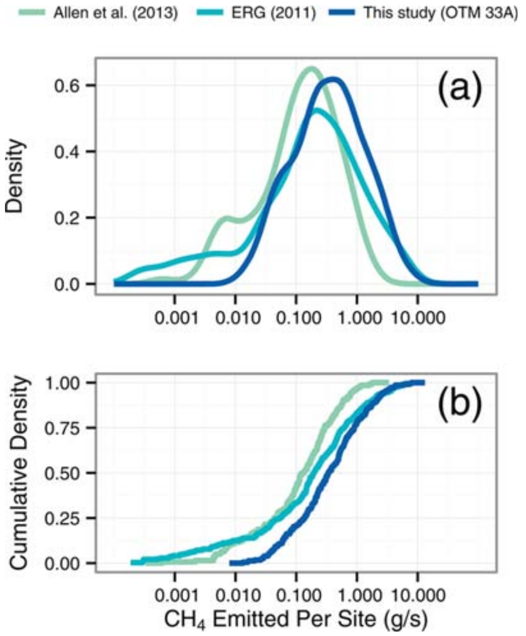

Figure 4. Density (a) and cumulative density (b) of measurements of CH_4 emission rates (g/s) from this study (OTM 33A), Allen et al.,[16] and ERG.[15] Note the logarithmic *x*-axis.

Comparison of Measurements with Production Values. CH_4 emissions from the direct measurement studies and OTM 33A were compared to monthly gas production using a linear regression on the log transformed data (Figure 5). Sites with gas production <1 Mscf/day or CH_4 emissions <0.0005 g/s were excluded from the analysis (five sites in the ERG study[15]). Gas production values explained more of the variation in the OTM 33A measurements than the measurements from the on-site studies, although variation in gas production still accounted for only 8.3% of the total variation in emissions ($R^2 = 0.083$) (Figure 5).

The OTM 33A CH_4 emission estimates were also compared with hydrocarbon liquids and water production and the (arithmetic) mean age of active permitted wells on the site using Pearson correlation coefficients (Table 1) and a multivariate linear regression.

Approximately 23% and 15% of the pads measured using OTM 33A reported no hydrocarbon liquids or water production, respectively. To use these pads in the log-transformed model, pads with no reported oil or water production were assigned 0.01 bbl/day. Several values were tested and the choice of this value did not significantly affect the results. When considering the correlation between production and emissions individually, CH_4 emissions were most strongly correlated with gas production ($R = 0.29$). CH_4 emissions were also positively correlated with water production, negatively correlated with mean age, and not correlated with hydrocarbon liquids production (Table 1).

A multivariate linear regression was conducted to determine the effect of gas and hydrocarbon liquids production and age of the well on CH_4 emissions simultaneously. Water production was not included in the model because it was so highly correlated with gas production ($R > 0.7$) that the effects could not be separated. The following model was used:

$$\log(CH_4) = \beta_1 \log(\text{gas}) + \beta_2 \log(\text{oil}) + \beta_3 \text{age} \qquad (1)$$

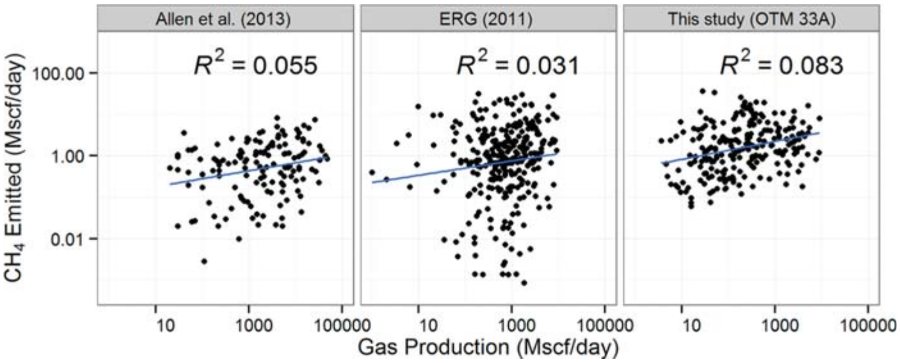

Figure 5. CH_4 emissions (Mscf/day) versus reported monthly gas production (Mscf/day). Blue lines represent the linear regression lines.

Table 1. Pearson Correlation Coefficients (R) of Emissions and Production

	CH_4 emissions (Mscf/day)	gas production (Mscf/day)	hydrocarbon liquids production (bbl/day)	water production (bbl/day)
CH_4 emissions (Mscf/day)	1.00			
gas production (Mscf/day)	0.29	1.00		
hydrocarbon liquids production (bbl/day)	−0.01	0.44	1.00	
water production (bbl/day)	0.22	0.77	0.40	1.00
mean age (years)	−0.20	−0.59	−0.34	−0.57

where CH_4 represents measured emissions in g/s, gas is total reported production in Mscf/day, oil is total reported hydrocarbon liquids production in bbl/day, and age is the mean age of the wells in years. Age was not significantly correlated with CH_4 emissions, while gas production was significantly positively correlated, and oil production was significantly negatively correlated (SI Table S2). The negative correlation with oil production is consistent across the basins (SI Figure S1). This negative correlation with oil production is likely due to the lower fraction of CH_4 in wet gas compared to dry gas. Furthermore, emissions from condensate tanks, which are more prevalent in wet gas areas, typically contain a lower fraction of CH_4 and higher fraction of heavier hydrocarbons such as VOCs when compared with produced gas.[6] The inclusion of hydrocarbon liquids and age in the model did not explain much more of the variation in emissions resulting in an adjusted R^2 of only 0.096, in contrast to an R^2 of 0.083 when only gas production was included (Figure 5).

Other important sources of variation not accounted for in this analysis include emissions controls and equipment present on the pads. Further uncertainty is introduced by the production data: daily or hourly production levels may not be consistent with monthly production.

Although the OTM 33A CH_4 emissions data include episodic features (e.g., flash emissions), it is instructive to compare emission rates as a percent of production with the measurements by Allen et al.[16] and ERG.[15] The differences between the CH_4 emissions estimates of the three studies are amplified when emissions are considered as a percentage of total production rather than in mass emission rate (SI Figure S2). For the sites measured using OTM 33A, approximately 0.72 (0.44, 1.17)%, 1.36 (0.97, 1.95) %, and 0.58 (0.39, 0.86) % of production was emitted on average (with 95% CI) in the Barnett, DJ, and Pinedale basins, respectively, compared with 0.11 (0.09, 0.16)% of production measured by ERG[15] in the Barnett shale and 0.01 (0.01, 0.01) % and 0.09 (0.04, 0.20)% measured by Allen et al.[16] in the Appalachian and Rocky Mountain basins, respectively (SI Figure S2). As evidenced in the statistical analysis, differences in production rate explain only a fraction of the variation in emissions. The percentages from this study only represent emissions from routine well pad operations and thus cannot be directly compared to other estimates of total CH_4 emitted as a percent of production such as those by Brandt et al.[5] that include emissions from many other processes.

Mean gas production at the OTM 33A sites was significantly lower than mean gas production at the sites measured in the direct measurement studies (SI Figure S4). Gas production at the OTM 33A sites ranged from 3.7 (Mscf/day) to 9021 (Mscf/day) with 37% of the sites producing <100 Mscf/day. In contrast, Allen et al.[16] reported a gas production range of 20 to 47 690 (Mscf/day) with only 10% of the sites producing <100 Mscf/day and with approximately 20% of the measured sites producing >10,000 Mscf/day. The gas production values of the ERG[15] sites ranged from 0.06 to 9085 Mscf/day in the Barnett with 10% of the sites producing <100 Mscf/day (SI Figure S4). The OTM 33A results indicate that sites with very low gas and oil production can emit a much greater fraction of the gas produced than sites with higher production levels. Maintenance issues (e.g., fugitive leaks, open or leaking thief hatches, failed pressure relief devices, malfunctioning separator dump valves) could be more prevalent at smaller older production sites than at higher producing sites that are potentially better maintained and may have fundamentally different engineering designs (e.g., use of buffer tanks to suppress flash emissions). Furthermore, many of the fugitive processes can emit at levels that are not linearly associated with production rates as is evidenced by the lack of correlation between emissions and production and the finding by Allen et al.[16] that equipment leaks are underestimated by the 2011 EPA national inventory.

In summary, the OTM 33A mobile inspection method can be used to complement direct measurement techniques and expand our knowledge of the upper range of the distribution of CH_4 emissions. OTM 33A was successfully applied to quantify CH_4 emissions at 210 oil and gas well pads with an accuracy of ±60% determined by controlled release tests. Well pad emissions were log-normally distributed and differed significantly by basin with geometric means ranging from 0.14 g/s in the Denver-Julesburg to 0.59 g/s in the Pinedale basin. Repeat measurements at 9 sites indicated consistent low emission rates at seven sites and highly variable emissions at two sites, one a documented malfunction. The production rates accounted for approximately 10% of the variation in sampled emission rates in a multivariate linear regression on age, hydrocarbon liquid and gas production. Normalizing emissions by gas production amplified the differences between the remote and onsite measurements. Compared to the direct measurements in the Barnett, the mean of the remote measurements was approximately twice as large in terms of mass emissions rate, but approximately seven times as large when considered as a percentage of production, indicating that sites with lower production levels can emit a much greater percentage of production. Infrared camera videos indicate that emission rates may be strongly affected by stochastic variables. In particular, equipment malfunctions or operator error may cause emission rates to increase substantially compared to routine operating conditions. Accurately estimating site emissions on a regional scale likely will require determining the average magnitude and frequency of these stochastic events.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Supplemental figures, tables, and IR videos are supplied. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Moore, C. W.; Zielinska, B.; Petron, G.; Jackson, R. B. Air impacts of increased natural gas acquisition, processing, and use: A critical review. *Environ. Sci. Technol.* **2014**; DOI: 10.1021/es4053472.

(2) Roy, A. A.; Adams, P. J.; Robinson, A. L. Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas. *J. Air Waste Manage. Assoc.* **2014**, *64* (1), 19−37 DOI: 10.1080/10962247.2013.826151.

(3) CenSARA, 2011 Oil and Gas Emission Inventory Enhancement Project for CenSARA. *States prepared for: Central States Air Resources Agencies* 2011. http://www.censara.org/filedepot_download/56064/14 (accessed September 17, 2014).

(4) Field, R. A.; Soltis, J. J.; Murphy, S. Air quality concerns of unconventional oil and natural gas production. *Environ. Sci.: Processes Impacts* **2014**, *16*, 954−969 DOI: 10.1039/C4EM00081A.

(5) Brandt, A.; Heath, G.; Kort, E.; O'Sullivan, F.; Pétron, G.; Jordaan, S.; Tans, P.; Wilcox, J.; Gopstein, A.; Arent, D. Methane leaks from North American natural gas systems. *Science* **2014**, *343* (6172), 733−735 DOI: 10.1126/science.1247045.

(6) Hendler, A.; Nunn, J.; Lundeen, J.; McKaskle, R. *VOC Emissions from Oil and Condensate Storage Tanks*; Houston Advanced Research Center, 2006; http://files.harc.edu/Projects/AirQuality/Projects/H051C/H051CFinalReport.pdf.

(7) Gidney, B.; Pena, S. *Upstream Oil and Gas Storage Tank Project Flash Emissions Models Evaluation Final Report*; Texas Commission on Environmental Quality: Austin, TX, 2009; http://www.bdlaw.com/assets/htmldocuments/TCEQ%20Final%20Report%20Oil%20Gas%20Storage%20Tank%20Project.pdf.

(8) U.S. EPA. *Greenhouse Gas Reporting Rule Subpart W, Petroleum and Natural Gas Systems*; Public Law 78 FR 71904, 2013; http://www.gpo.gov/fdsys/pkg/FR-2013-11-29/pdf/2013-27996.pdf.

(9) U.S. EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990−2011*; EPA 430-R-13-001, 2013; http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2013-Main-Text.pdf.

(10) U.S. EPA. *EPA Needs to Improve Air Emissions Data for the Oil and Natural Gas Production Sector*; Report No. 13-P-0161; U.S. Environmental Protection Agency Office of Inspector General: Washington DC, 2013; http://www.epa.gov/oig/reports/2013/20130220-13-P-0161.pdf.

(11) Snyder, E. G.; Watkins, T. H.; Solomon, P. A.; Thoma, E. D.; Williams, R. W.; Hagler, G. S.; Shelow, D.; Hindin, D. A.; Kilaru, V. J.; Preuss, P. W. The changing paradigm of air pollution monitoring. *Environ. Sci. Technol.* **2013**, *47* (20), 11369−11377 DOI: 10.1021/es4022602.

(12) Caulton, D. R.; Shepson, P. B.; Santoro, R. L.; Sparks, J. P.; Howarth, R. W.; Ingraffea, A. R.; Cambaliza, M. O.; Sweeney, C.; Karion, A.; Davis, K. J. Toward a better understanding and quantification of methane emissions from shale gas development. *Proc. Natl. Acad. Sci. U. S. A.* **2014**, *111* (17), 6237−6242 DOI: 10.1073/pnas.1316546111.

(13) Karion, A.; Sweeney, C.; Pétron, G.; Frost, G.; Michael Hardesty, R.; Kofler, J.; Miller, B. R.; Newberger, T.; Wolter, S.; Banta, R. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophys. Res. Lett.* **2013**, *40* (16), 4393−4397 DOI: 10.1002/grl.50811.

(14) Thoma, E.; Squier, B.; Olson, D.; Eisele, A.; DeWees, J.; Segall, R.; Amin, M.; Modrak, M. Assessment of methane and voc emissions from select upstream oil and gas production operations using remote measurements, interim report on recent survey studies. In *Proceedings of 105th Annual Conference of the Air & Waste Management Association*, Control No. 2012-A-21-AWMA, 2012, 298−312.

(15) ERG. City of Fort Worth Natural Gas Air Quality Study Final Report; Fort Worth, TX, 2011. http://fortworthtexas.gov/gaswells/?id=87074.

(16) Allen, D. T.; Torres, V. M.; Thomas, J.; Sullivan, D. W.; Harrison, M.; Hendler, A.; Herndon, S. C.; Kolb, C. E.; Fraser, M. P.; Hill, A. D. Measurements of methane emissions at natural gas production sites in the United States. *Proc. Natl. Acad. Sci. U. S. A.* **2013**, *110* (44), 17768−17773 DOI: 10.1073/pnas.1304880110.

(17) U.S. EPA. Other Test Method (OTM) 33 and 33A Geospatial Measurement of Air Pollution-Remote Emissions Quantification-Direct Assessment (GMAP-REQ-DA). 2014. (http://www.epa.gov/ttn/emc/prelim.html).

(18) Golder, D. Relations among stability parameters in the surface layer. *Bound.-Lay. Meteorol.* **1972**, *3* (1), 47−58 DOI: 10.1007/BF00769106.

(19) Google Inc. Google Earth Pro (Version 7.1.2.2041), 2014.

(20) ESRI. *ArcGIS Desktop: Release 10*; Environmental Systems Research Institute: Redlands, CA, 2011.

(21) *Public GIS Map Viewer for Oil, Gas, and Pipeline Data*. http://wwwgisp.rrc.state.tx.us/GISViewer2/ (April 22, 2014),.

(22) COGCC GIS Online. http://dnrwebmapgdev.state.co.us/mg2012app/ (accessed April 22, 2014).

(23) R Core Team *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2013.

(24) Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*; Springer: New York, 2009.

(25) Harrell Jr, F. E.; Dupont, C. Hmisc R package version 3.14-1. 2007.

(26) TX RRC. Texas Administrative Code. Title 16 Part 1 Chapter 3 Rule §3.79, Railroad Commission of Texas, Oil and Gas Division: Austin, TX, http://info.sos.state.tx.us/pls/pub/readtac$ext.TacPage?sl=R&app=9&p_dir=&p_rloc=&p_tloc=&p_ploc=&pg=1&p_tac=&ti=16&pt=1&ch=3&rl=79.

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Field Measurements of Fugitive Emissions from Equipment and Well Casings in Australian Coal Seam Gas Production Facilities

Report to the Department of the Environment

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June 2014

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Important disclaimer

Contents

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Executive Summary

The Australian coal seam gas (CSG) industry has developed rapidly over the last decade and as several liquefied natural gas (LNG) plants currently under construction in Queensland are completed, gas production will increase significantly over the next few years. Fugitive emissions of methane from gas production and processing have the potential to diminish the greenhouse benefits of CSG utilisation compared to other fossil fuels but at present the extent of fugitive emissions from the CSG industry and unconventional gas production more generally is not well understood. Recent reports from the United States have suggested that fugitive emissions from unconventional gas production, especially shale and tight gas, are much higher than previously estimated. However, because of significant differences in production methods and other factors, it is unlikely that emission estimates from U.S. shale and tight gas production are indicative of emissions from Australian CSG operations. To provide quantitative information on emissions from CSG operations, CSIRO and the federal Department of the Environment initiated a project to measure emissions from a range of production wells in Queensland and NSW.

Methane emissions were measured at 43 CSG wells – six in NSW and 37 in Queensland. Measurements were made by downwind traverses of well pads using a vehicle fitted with a methane analyser to determine total emissions from each pad. In addition, a series of measurements were made on each pad to locate sources and quantify emission rates.

Of the 43 wells examined, only three showed no emissions. These were two plugged and abandoned wells and one suspended well that had been disconnected from the gas gathering system. The remainder had some level of emission but generally the emission rates were very low, especially when compared to the volume of gas produced from the wells. The principal methane emission sources were found to be:

- venting and operation of gas-powered pneumatic devices,
- equipment leaks and
- exhaust from gas-fuelled engines used to power water pumps.

The median methane total emission rate (from all sources) for the 43 wells was approximately 0.6 g min^{-1}, and the mean about 3.2 g min^{-1}. Thirty seven wells had total emissions less than 3 g CH_4 min^{-1} and 19 less than 0.5 g min^{-1}. There were however, a number of instances where much higher emission rates were found. The highest emission rate of 44 g min^{-1} was from a vent on a water line at one well although this represented a very minor proportion of gas production. These emission rates are very much lower than those that have been reported for U.S. unconventional gas production.

Gas operated pneumatic devices were installed at some well sites and were occasionally found to be emitting small amounts of methane. These emissions were small (mean emissions rate of 0.12 g min^{-1}) and may reduce even further as gas operated pneumatic systems are replaced by air or electrically operated devices.

Equipment leaks were found on 35 wells with emission rates ranging from less than 1 mg min^{-1} up to about 28 g min^{-1}. The median and mean emission rates from these wells were 0.02 g min^{-1} and 1.6 g min^{-1}, which correspond to emission factors of about 0.1 kg CO_2-e t^{-1} and 2.4 kg CO_2-e t^{-1}, respectively. This range is consistent with the current emission factor of 1.2 kg CO_2-e t^{-1} commonly used throughout the CSG industry to account for equipment leaks for the purposes of reporting emissions under the National Greenhouse and Energy Reporting legislation.

Several of the larger equipment leaks were found at seals on water pump shafts on some wells. However, once identified, well maintenance staff were able to repair some of these leaks on site, which effectively eliminated methane emissions.

Fifteen of the well sites had gas fuelled engines operating at the time measurements were made. The exhaust from most of these engines was found to be contributing to the well site emissions, in several cases comprising the bulk of methane emissions. From a greenhouse gas accounting perspective, methane in exhaust is not considered to be a fugitive emission but is counted as a combustion emission.

During the field measurements, no evidence of leakage of methane around the outside of well casings was found at any of the wells included in this sample.

Although the well pad emissions were low, a separate, larger source of methane was found on a gas relief vent on a water gathering installation close to one of the wells examined during this study. An indicative estimate of the emission rate from this vent suggested that the source was at least three times higher than the largest well pad emission rate. Similar installations are widespread through the Queensland gas regions and hence further examination is needed to determine the extent of this potential emission source.

The results obtained in this study represent the first quantitative measurements of fugitive emissions from the Australian CSG industry; however, there are a number of areas that require further investigation. Firstly, the number of wells examined was only a very small proportion of the total number of wells in operation. Moreover, many more wells are likely to be drilled over the next few years. Consequently the small sample examined during this study may not be truly representative of the total well population. It is also apparent that emissions may vary over time, for instance due to repair and maintenance activities. To fully characterise emissions, a larger sample size would be required and measurements would need to be made over an extended period to determine temporal variation.

In addition to wells, there are many other potential emission points throughout the gas production and distribution chain that were not examined in this study. These include well completion activities, gas compression plants, water treatment facilities, pipelines and downstream operations including LNG facilities. Emissions from some of these sources are often estimated for reporting purposes using methodology based on emission factors largely derived from the U.S. gas industry. However, reliable measurements on Australian facilities are yet to be made and the uncertainty associated with some of these estimates remains high.

1 Introduction

Coal seam gas (CSG) production is a major and rapidly expanding industry in Australia. During 2011-2012, Australian CSG production was around 247 PJ, which represented about 12 % of total gas production in Australia (BREE, 2013). Since then, production in Queensland alone has increased to more than 264 PJ in 2012-2013 (DNRM, 2014) with production likely to increase even further as several liquefied natural gas plants under construction come on stream. Most Australian CSG is currently produced in Queensland with only one operational project in NSW; however, there are a number of other projects planned for NSW at various stages of approval.

One of the key drivers of increased demand for gas is that greenhouse gas emissions from gas utilisation are usually lower than other fossil fuels (Day et al., 2012). However, because of the much higher global warming potential of methane compared to CO_2, even relatively small proportions of fugitive methane released during the production, processing and distribution of natural gas can reduce this advantage relative to other fuels (e.g. Wigley, 2010; Alvarez et al., 2012).

In the natural gas industry, fugitive emissions are considered to include all greenhouse gas emissions from exploration, production, processing, transport and distribution of natural gas, except those from fuel combustion (IPCC, 2006). However certain combustion processes like flaring and waste gas incineration are also counted as fugitive emissions.

At present the level of fugitive emissions from the Australian CSG industry is not well defined, although individual companies estimate and report their annual emissions under the requirements of the National Greenhouse and Energy Reporting Act 2007 (NGER, see Section 2). These data are used for compiling the Australian National Greenhouse Gas Inventory which currently estimates fugitive emissions from the Australian oil and gas industry to be around 12 Mt CO_2-e per annum (DIICCSRTE, 2013a). About 60 % of these emissions are attributed to venting and flaring, which are in principle amenable to direct measurement; hence the uncertainty on this component may be relatively low. However, other sources such as equipment leaks are frequently difficult to measure so are usually estimated by methodology characterised by very high uncertainty. Despite significant differences in production methods, the national inventory does not at present distinguish between conventional gas production and unconventional sources like shale gas and CSG.

In 2012, the CSIRO reviewed the available scientific and technical literature to assess the current state of knowledge relating to fugitive emissions from unconventional gas production, especially for CSG production in Australia (Day et al., 2012). Most of the information in the public domain at the time was concerned with shale and tight gas production in the United States with virtually none specific to CSG. Up until then, only one study based on actual measurements had been published (Pétron et al., 2012). This group measured methane emissions in the Denver-Julesburg Basin in Colorado and depending on the method used, estimated that the emission rate from the gas field was equivalent to 1.7 to 7.7 % of the gas produced in the region.

Since 2012, several other studies, also from the United States, have been published. Karion et al. (2013) conducted an airborne survey of ambient methane in an unconventional gas field in the Uintah Basin in Utah in the United States. The Karion et al. study yielded emission estimates of between about 6 and almost 12 % of gas production of the region. In a detailed examination of atmospheric methane data from airborne and fixed monitoring stations, Miller et al. (2013) determined the spatial distribution of methane emissions throughout the United States. This study considered all sources of anthropogenic methane emissions, including fugitive emissions from oil and gas production. For the Texas/Oklahoma region emissions from oil and gas production were estimated to be 3.7 ± 2.0 Tg C y^{-1}, which is 4.9 ± 2.6 times higher than the current estimate of 0.75 Tg C y^{-1} in the European Commission's Emissions Database for Global Atmospheric Research (EDGAR).

Both the Miller et al. (2013) and Karion et al. (2013) studies used top-down methodology and did not attempt to determine the specific sources of the methane emissions. Pétron et al. (2012) also used top-down methods which yielded the higher estimates (i.e. ~7.7 % of production) although the bottom-up methodology used by that group gave much lower emission estimates (1.7 %). A bottom-up approach was used by Allen et al. (2013) who examined emissions at the facility level to determine both the rate and route of methane emission. In that study, methane emissions were measured at 190 onshore natural gas sites within the United States, which included 489 production wells (all of which had been hydraulically fractured), 27 well completion flowbacks, nine well unloadings, and four well workovers. One of the key findings of this work was that the measured emissions were generally comparable to the most recent USEPA estimates of emissions from the sources examined, although the relative proportion of emissions from individual categories differed somewhat. For example, emissions from pneumatic devices were significantly higher than current estimates while emissions from well completions were much lower than estimates in the U.S. inventory. Overall, the emissions estimated from the unconventional gas industry corresponded to about 0.42 % of production.

This bottom-up estimate contrasts with the much higher top-down estimates discussed above. The lower emission rate estimated by Allen et al. (2013) may be explained in part by the fact that only production facilities were considered. Emissions from downstream processing, transport and distribution were not included so any emissions from these facilities would be expected to increase this proportion. Another reason for the discrepancy between bottom-up and top-down estimates has been proposed by Brandt et al. (2014) who suggested that a large proportion of emissions may be due to a small number of 'super emitters'. If true, facility level bottom-up measurements may sometimes miss these large emission sources. In addition to gas production facilities, other sources may be contributing to overall emissions, which are not captured by the bottom-up methods. Tait et al. (2013), for example, proposed that drilling and associated activity may induce fracturing of overlying strata thus providing pathways for methane to reach the surface and escape to the atmosphere. Such landscape-scale emissions would be detected by many top-down methods but may be difficult to measure using the bottom-up methodology applied by Allen et al. (2013). However, the Tait et al. (2013) model was based on ambient radon measurements; methane emission rates were not measured so this emission route remains speculative at this stage. Other possible emission sources that could account for the apparent discrepancy between the reported top-down and bottom-up methods are geological sources such as seeps that are often associated with oil and gas fields (Klusman, 1993) or abandoned boreholes (Etiope et al., 2013; Day et al., 2013).

In Australia, limited investigations into fugitive methane emissions from CSG production have been undertaken over the last couple of years. In an initial study that was widely reported, Santos and Maher (2012) surveyed a CSG production region near Tara in Queensland using an instrumented vehicle to measure the spatial distribution of ambient methane concentrations. They measured elevated methane concentrations within the gas field that they suggested may be indicative of fugitive methane release from production activities. More recently, a study of ambient methane levels in the vicinity of CSG production facilities south of Sydney was reported (Pacific Environment Limited, 2014). This study also found elevated methane concentrations near CSG facilities although they concluded that on average, ambient methane concentrations within the gas field were comparable to those in a nearby urban area. However, neither study attempted to measure emission flux and in any case, the presence of other potential methane sources such as cattle feedlots, abandoned boreholes and landfill sites complicated the interpretation of the results. Consequently attempts to attribute sources based on these results remain inconclusive.

Despite the level of recent activity aimed at quantifying emissions from unconventional gas production, the situation remains unclear. The Australian studies reported to date only considered ambient methane concentrations near gas production sites and provide no information on emission flux. While the U.S. studies measured emission rates, widely varying estimates were reported. Moreover, they were concerned with shale and tight gas operations, which are unlikely to be indicative of emissions from Australian CSG production facilities. Due to the lack of quantitative emission data specific to Australian operations, the CSIRO review recommended, among other things, that a series of measurements at CSG production facilities was required to better understand the actual level of fugitive emissions from the Australian CSG industry (Day et al., 2012). A similar recommendation for emissions measurements was made by Saddler (2012) when reviewing methodology for estimating emissions from CSG production.

As a result of these recommendations, CSIRO initiated a project with the principal aims of (1) developing atmospheric top-down methodology for monitoring and quantifying methane fluxes from CSG production facilities and (2) measuring methane emission fluxes from operational CSG production sites. Shortly after this project commenced, the federal Department of the Environment (then the Department of Climate Change and Energy Efficiency) requested that CSIRO to extend the scope of the field measurements to include an investigation of gas leakage from well casings and equipment located on individual well pads.

In this report we present the results of field measurements made at well sites throughout NSW and Queensland. The specific objectives of these measurements were to:

- quantify methane emissions from individual well pads,
- identify the primary routes of these emissions,
- measure leak rates from individual items of equipment located on well pads and
- determine whether or not methane was leaking from around the outside of well casings and if so, measure the leakage rate.

While wells represent a major segment of the CSG production infrastructure, it is important to note that there are many other components downstream of the wells which have the potential to release greenhouse gases. These include processing and compression plants, water treatment facilities, gas gathering networks, high pressure pipelines and several LNG production facilities currently under construction near Gladstone. In the study reported here, we have only examined emissions from a small sample of CSG wells; none of the other downstream infrastructure has been considered at this stage. However, the ongoing CSIRO research into atmospheric top-down method methodology is aimed at developing techniques for monitoring emissions across the CSG industry more broadly.

2 National Greenhouse Gas Reporting Practices

Before discussing the experimental results of the field measurements it is instructive to consider the methodology currently used to estimate greenhouse gas emissions from CSG wells.

Australian CSG gas producers (along with conventional gas operators) are required to estimate and report their annual greenhouse emissions in accordance with the National Greenhouse and Energy Reporting Act 2007 using methodology prescribed in the National Greenhouse and Energy Reporting (Measurement) Determination 2008. The scope of the Act covers all sectors of the gas industry i.e. production and processing, transmission and distribution, and includes emissions from fuel combustion (e.g. stationary engines at well sites and compression plants) and fugitive emissions (leaks from equipment, venting and flaring).

According to the definition used in the Determination, fugitive emissions associated with natural gas production and processing comprise:

- Emissions from venting and flaring
    - the venting of natural gas
    - the venting of waste gas and vapour streams at facilities that are constituted by natural gas production or processing
    - the flaring of natural gas, waste gas and waste vapour streams at those facilities
- Emissions other than venting and flaring which include
    - a gas wellhead through to the inlet of gas processing plants
    - a gas wellhead through to the tie-in points on gas transmission systems, if processing of natural gas is not required
    - gas processing plants
    - well servicing
    - gas gathering
    - gas processing and associated waste water disposal and acid gas disposal activities

The Determination specifies methodology for estimating emissions from all of these sources; the 'Methods' are broadly classified into four generic categories of varying complexity, which are briefly described below.

- Method 1 is the simplest approach and relies on activity data and an emission factor for the process. The emission factors used in Method 1 are generic and are usually specified in the NGER Determination.
- Method 2 is more specific and uses emission factors based on more detailed data.
- Method 3 is very similar to Method 2 except that the methods are based on internationally accepted standards.
- Method 4 is the direct measurement of emissions.

Some emissions can be directly measured (i.e. Method 4) but often emissions cannot be readily measured so instead, simpler methodology based on the concept of emission factors is used.

Emission factors are average emission rates of a particular gas (i.e. methane but also CO_2 and N_2O if applicable) from a given source. Emissions, *E*, are calculated by multiplying the emission factor, *EF*, by the activity of the process producing the emissions, *A* (Equation 2.1).

$$E = EF \times A \qquad \text{Equation 2.1}$$

Examples of activity are the amount of fuel consumed or the amount of gas produced.

This methodology can yield accurate emission estimates for processes such as fuel combustion where both the emission factor (which is based on the chemical composition of the fuel) and the activity data (i.e. consumption rate of fuel, which is often known to a high level of accuracy) can be well defined. However, for some fugitive emissions sources such as equipment leaks, emission factors may be subject to very high uncertainty. For instance, the American Petroleum Institute's Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry which provides emission factors for calculating emissions from gas production and processing operations, estimates that uncertainties on some emission factors may be as much as 1000 % (API, 2009). One of the reasons for this high level of uncertainty is that emission factors are often based on very limited experimental data.

CSG well pads may release greenhouse gases from a range of sources, all of which are estimated for annual reporting purposes. These sources include fuel combustion in well site engines used to drive water pumps, and fugitive emissions from vents, gas operated pneumatic devices and leaks in equipment. Occasionally, during maintenance operations for example, gas may be flared and this too counts as a fugitive emission that is accounted for. Combustion emissions from engines or flaring are predominantly CO_2 although small amounts of methane (unburnt fuel) and N_2O (produced in the combustion process) may also be emitted. Most of the other non-combustion emissions are methane.

Some emissions from vents can be measured according to Method 4 but because of its simplicity, many CSG operators use the Method 1 approach for estimating most of the other greenhouse gas emissions from well pads. The methods are summarised in Table 2.1.

Table 2.1. Summary of NGER estimation methods for various well pad sources

Classification	Source	Method
Fuel Combustion	Exhaust emissions from well site engines	Emission factor to account for CO_2, CH_4 and N_2O emissions: 51.2 kg CO_2-e GJ^{-1} (CO_2) 0.1 kg CO_2-e GJ^{-1} (CH_4) 0.03 kg CO_2-e GJ^{-1} (N_2O)
Fugitive Emissions	Flare	Emissions factor to account for CO_2, CH_4 and N_2O emissions: 2.7 t CO_2-e t^{-1} (CO_2) 0.1 t CO_2-e t^{-1} (CH_4) 0.03 t CO_2-e t^{-1} (N_2O)
Fugitive Emissions	Equipment leaks	Emission factor of 1.2 kg CO_2-e t^{-1} gas produced
Fugitive Emissions	Gas driven pneumatic equipment	Emission factors specified in the API Compendium (API, 2009)
Fugitive Emissions	Cold process vents	In some cases these can be measured directly (i.e. Method 4). Otherwise estimated using emission factors in API Compendium.

Although most of the methods shown in Table 2.1 are based on the use of emission factors, the level of uncertainty associated with the estimates is quite variable. In the case of emission from engines, the uncertainty is likely to be relatively low provided the amount of fuel consumed is known accurately (which is usually the case). Similarly emissions from flaring can be estimated with reasonable accuracy if the gas flow to the flare is measured. Emissions from vents are often measured using process instrumentation so these too should be known with a high degree of certainty. Emissions from equipment leaks, pneumatic equipment and vents estimated by emission factors, on the other hand, have higher levels of uncertainty. However, the overall uncertainty of emission inventories is also influenced by the relative contribution of various sources. Hence if a source with high uncertainty comprises only a small proportion of total emissions from a particular sector, the overall level of uncertainty is not greatly influenced by the minor component.

3 Experimental Methods

3.1 Selection of Wells

Five CSG companies provided access to wells in various gas fields throughout NSW and Queensland, which are summarised in Table 3.1. Each company usually provided CSIRO with a list of their wells from which CSIRO staff selected a subset of wells for examination. Because individual companies agreed to participate in the project at different times during the course of the project it was not possible to make a properly randomised selection of wells at the start of the project. Instead, wells were selected on an ad hoc basis in the order that companies agreed to participate. In addition, access to sites due to weather and agreements with landholders determined the selection of wells to some extent.

Factors considered when selecting wells included:

- The production region
- The age of the well, i.e. old to new
- The gas production rate, i.e. from low to high rates
- Whether or not the well had been hydraulically fractured
- The type of surface equipment installed at the well, i.e. pumped or free flowing.

Table 3.1. Participating CSG producers and the gas fields where emission measurements were made.

Company Name	Project Name	Basin	Locality
AGL Energy Limited	Camden	Sydney	MacArthur region, NSW
Arrow Energy Limited	Daandine	Surat	Dalby area, Qld
	Kogan North	Surat	Dalby area, Qld
	Tipton	Surat	Dalby area, Qld
Origin Energy Limited	Talinga	Surat	Chinchilla area, Qld
QGC Pty Limited	Bellevue	Surat	Chinchilla area, Qld
	Berwyndale	Surat	Chinchilla area, Qld
	Berwyndale South	Surat	Chinchilla area, Qld
	Codie	Surat	Chinchilla area, Qld
	Kenya	Surat	Chinchilla area, Qld
	Lauren	Surat	Chinchilla area, Qld
Santos Limited	Fairview	Bowen	Injune area, Qld
	Scotia	Bowen	Wandoan area, Qld

For the purpose of this report, we consider the well pad to be the (usually) fenced area around a well head that contains the surface equipment associated with gas production. This includes the well head, dewatering pump (if fitted), separator, pipework and associated valves and fittings. Also included are vents, (including those installed on water gathering system components on the well pad) and engines used to power dewatering pumps.

The 43 wells selected represent less than 1 % of the 5,000 CSG wells across Australia and therefore may not be representative of the total well population. Nevertheless, it provides a reasonable cross section of the industry covering a range of different producers and geographic locations within the main gas production regions. For comparison, a recent study of well emissions in the U.S. where emissions measurements were made at 489 wells represented only about 0.01 % of U.S. unconventional gas wells (Allen et al., 2013).

3.2 Methane Analysis System

Methane measurements were made using a Picarro Model 2301 Cavity Ring-down Spectrometer $CH_4/CO_2/H_2O$ analyser coupled with a Picarro Mobile Measurement Kit. The resolution of this analyser is < 1 ppbv CH_4 and has very low drift characteristics (Crosson, 2008) so that very small CH_4 perturbations can be reliably detected against the background concentration. Both instruments were mounted in a 19” rack in the rear of a 4WD vehicle (Figure 3.1).

Figure 3.1. Photographs of the field vehicle where the GPS antenna and sonic anemometer are visible on the top of the vehicle (left hand photograph). The methane analyser and a calibration gas cylinder are shown in the rear of the vehicle (right hand photograph).

The Mobile Kit included a GPS receiver and software that allows the spectrometer output to be processed and displayed in GIS software. A two-dimensional sonic anemometer (Climatronics Sonimometer) was also fitted for measuring local wind speed during plume traversing measurements (Section 3.3).

For mobile surveys, the spectrometer was operated continuously as the vehicle was driven. Air was sampled via a ¼” nylon tube from the front of the vehicle about 1 m above ground level. The normal flow rate of sample air to the spectrometer is approximately 100 mL min^{-1}; however, to minimise the lag time between air entering the inlet tube and reaching the analyser, an auxiliary pump in the Mobile Kit was used to increase the flow rate to about 5 L min^{-1}. When used for flux chamber measurements (Section 3.5), the auxiliary pump was bypassed using a three-way valve.

Initially, the instrument was configured to measure CH_4, CO_2 and H_2O simultaneously; however, the sampling rate in this mode was relatively slow with measurements made approximately every 3 s. To increase the spatial resolution during plume traverses, the sampling rate was increased to about 2 Hz by reconfiguring the analyser to measure CH_4 only.

The analyser was calibrated against a reference air sample containing 1.732 ppm CH_4 prepared by the CSIRO Marine and Atmospheric Research GASLAB (Francey et al., 2003). Additional standard gas mixtures of 10.2 and 103 ppm CH_4 in air (BOC Gases Australia) were used for multipoint calibrations.

Although the nominal range of the analyser is 0-20 ppm CH_4, we found that the instrument could reliably measure concentrations well in excess of this level. In one experiment, an Ecotech GasCal dilution system was used to generate gas flows with known CH_4 concentrations up to about 280 ppm. The results of this experiment are shown in Figure 3.2 where the analyser output is plotted against the actual methane concentration.

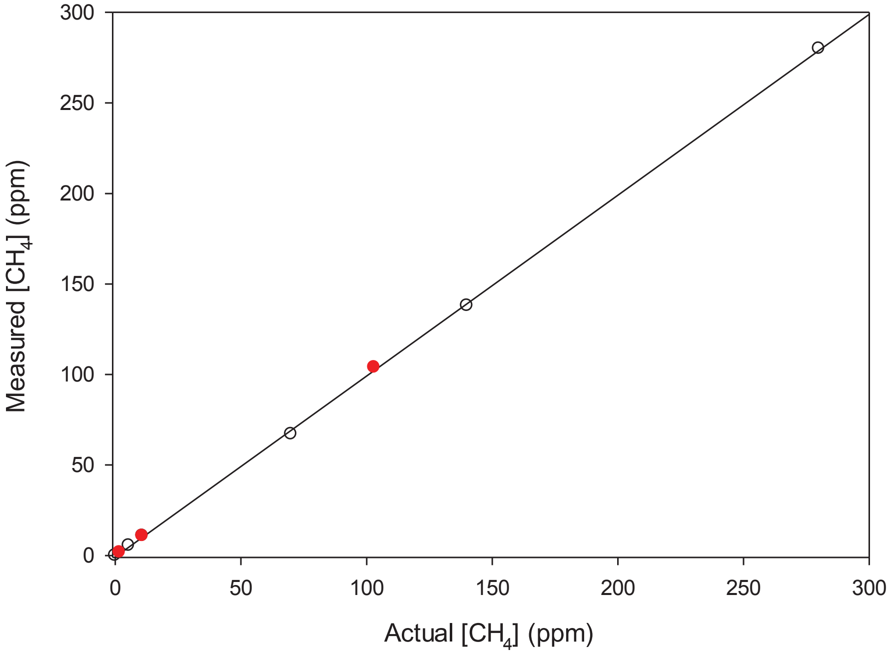

Figure 3.2. Calibration curves obtained for the methane analyser. Open circles correspond to points made using gas mixtures generated with a gas diluter. Red circles represent a multipoint calibration made using reference gases several months later.

The response of the instrument remained linear at least to 280 ppm CH_4. One of the routine multipoint calibration curves using the three reference gases made several months later (red markers) is also plotted to demonstrate the low drift characteristics of the instrument.

Multipoint calibrations were performed before and after each field campaign and single point calibration checks were made periodically in the field.

3.3 Plume Traverses

Methane emissions from well pads were estimated using a plume dispersion method. In this method, the CH_4 concentration profile in a plume originating from CH_4 emission sources on the pad is measured at some distance downwind of the pad by performing traverses across the plume. Since the plume comprises all CH_4 released from the pad, it yields total emissions from each pad. The technique is illustrated in Figure 3.3.

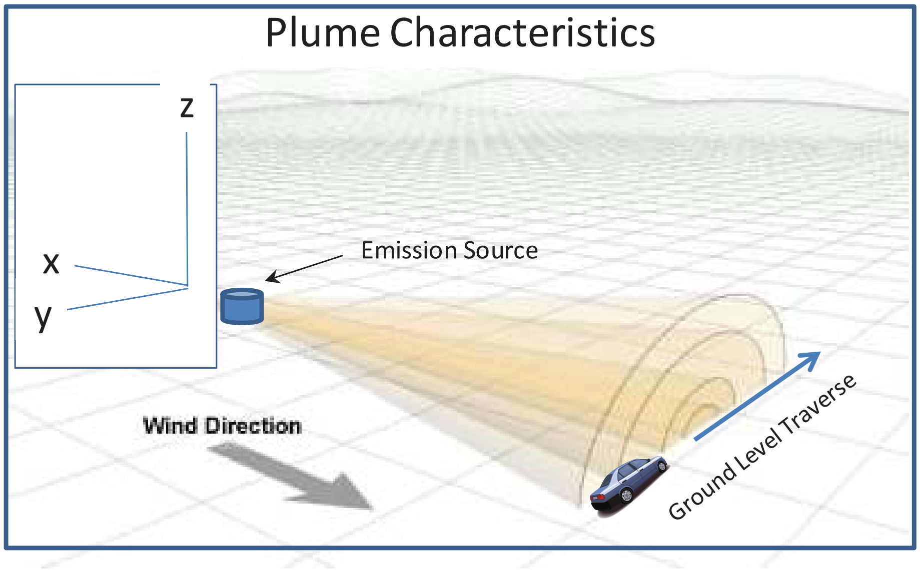

Figure 3.3. Schematic representation of the plume traversing experiments.

The field vehicle with the CH_4 analyser was driven 15 to 50 m downwind of each well to measure the ground level CH_4 concentration across each plume. The emission flux, *F*, over each traverse was estimated by integrating the CH_4 concentration enhancement (i.e. the measured concentration minus background CH_4 concentration), *c*, of the plume in the horizontal and vertical directions and multiplying by the average wind velocity, *u*, measured at each site (Equation 3.1). Background CH_4 concentrations were measured by performing upwind traverses of the well pad.

$$F = u \int_{-y}^{y} \int_{0}^{z} c(y,z)\,dy\,dz \qquad \text{Equation 3.1}$$

Since the traverse measurements were made at ground level only, the vertical extent was estimated by reference to the Pasquill-Gifford curves of σ_z (i.e. the standard deviation of the distribution of CH_4 concentration in the vertical direction) as a function of downwind distance under given atmospheric turbulence conditions (Hanna et al., 1982). The vertical concentration profile of CH_4, within the plume was assumed to decrease from the ground level concentration with height according to a Gaussian distribution across the traverse plane. For each well, an average emission rate was determined from up to 10 traverses made over about a 20-minute period.

One of the primary sources of uncertainty with the plume traversing method is associated with determining the height of the plume because it must be estimated rather than measured. To assess the level of uncertainty in the plume traversing results, we performed a number of experiments where CH_4 was released from a cylinder of compressed gas at a known rate while traverses were made downwind of the source. The results of the traverses were then compared with the actual rate of CH_4 release. These controlled release measurements were made at a site near the CSIRO laboratories in Newcastle where there were no other sources of CH_4 present and to simulate field conditions, traverses were made between 15 and 50 m downwind of the controlled release point. The results of these experiments are discussed in Section 4.1.

3.4 Leak and Vent Testing

At each well site an initial survey for elevated CH_4 concentrations was made by performing vehicle traverses as described above to determine if CH_4 emissions were present. The presence of elevated CH_4 concentrations indicated some type of leak, venting or engine exhaust emission from the pump power pack. Where CH_4 was detected, more detailed examination of the facility was undertaken using a probe connected to the vehicle mounted CH_4 analyser to locate the source or sources of CH_4 (Figure 3.4). On some occasions, leaks were located by spraying a leak detection solution (Snoop, Swagelok Company) onto individual components.

Figure 3.4. Locating equipment leaks at a CSG well pad.

When the source of the leak was identified, the leak rate was measured. During the first set of field measurements, leak rates were measured in accordance with the USEPA Protocol for Equipment Leak Emission Estimates (USEPA, 1995). In this procedure, the leaking component is enclosed in a plastic bag or sleeve and an air stream is passed through the bag at a known rate while the outlet stream is analysed for CH_4 concentration. Although this is a proven method for quantifying leak rates, it was found to be very slow and labour intensive. For later measurements (and the majority of the results reported here) we constructed a high-flow apparatus, similar in principle to the 'Hi-Flow' device reported by Kirchgessner et al. (1997). In this system, a high capacity fan attached to a 100 mm diameter flexible tube was used to provide an air stream around the leak point to entrain the leaking CH_4. A variable power supply was used to allow the fan speed to be varied up to a maximum flow rate of approximately 80 L s^{-1} (4.8 m^3 min^{-1}).

During leak tests, the inlet of the hose was held within about 150 mm of the apparent leak point while the CH_4 concentration in the outlet air stream was measured with the CH_4 analyser in the field vehicle. The leak rate, R_l, was calculated from the volumetric flow rate of the air stream, V, and the steady state CH_4 concentration, c, according to Equation 3.2

$$R_l = V \times c \qquad \text{Equation 3.2}$$

A schematic diagram of the apparatus is shown in Figure 3.5.

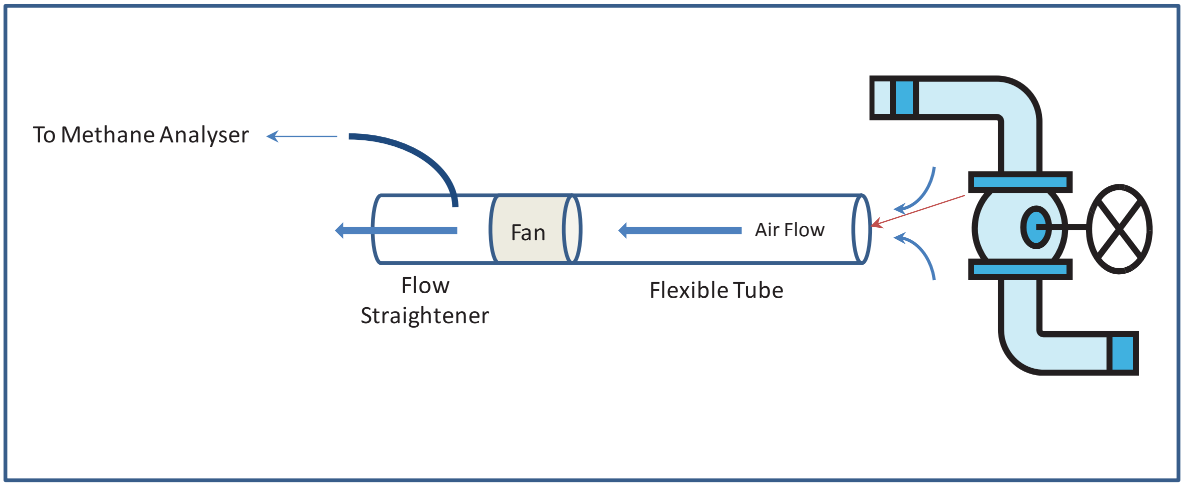

Figure 3.5. Schematic diagram of the leak testing apparatus. Methane leaking from a component (red arrow) is entrained in the airstream drawn into the tube by the fan.

Occasionally emission rates from some sources (e.g. vents and pneumatic devices) were amenable to a simple measurement technique where the exhaust point was sealed in a plastic bag of known volume and measuring the time required to fill the bag. In a few cases where the emission rate was reasonably constant, emission rates were measured by attaching a flow calibrator (DryCal DR2) to the emission outlet.

3.5 Surface Emissions

Measurements were made on the ground surface near well heads to determine if CH_4 was migrating around the outside of well casings or through casing walls. These measurements were made using a surface flux chamber, a technique frequently used to measure emission rates of soil gases. For these measurements, a plastic cylindrical chamber 37.5 cm in diameter and 40 cm high with a total volume of about 45 L and an area of coverage of 0.11 m^2 was placed on the ground at each sampling point. A small solar powered fan mounted in the chamber ensured that the sample within the chamber was well mixed during each experiment. The chamber was connected to the CH_4 analyser in the field vehicle via a ¼” nylon tube and the CH_4 concentration within the chamber, *C*, continuously measured over a period of several minutes. The flow rate of the sample stream from the flux chamber to the analyser was approximately 100 mL min^{-1}.

The CH_4 emission flux, *F*, was calculated according to Equation 3.3

$$F = \text{—}^{\cdots}\ \text{Ħ}^{\vee}_{''}$$

Equation 3.3

where *V* is the volume of the chamber, *dC/dt* is the rate of change in the CH_4 concentration over time, *t*, and *A* is the area of surface covered by the chamber.

A schematic diagram of the chamber system is shown in Figure 3.6

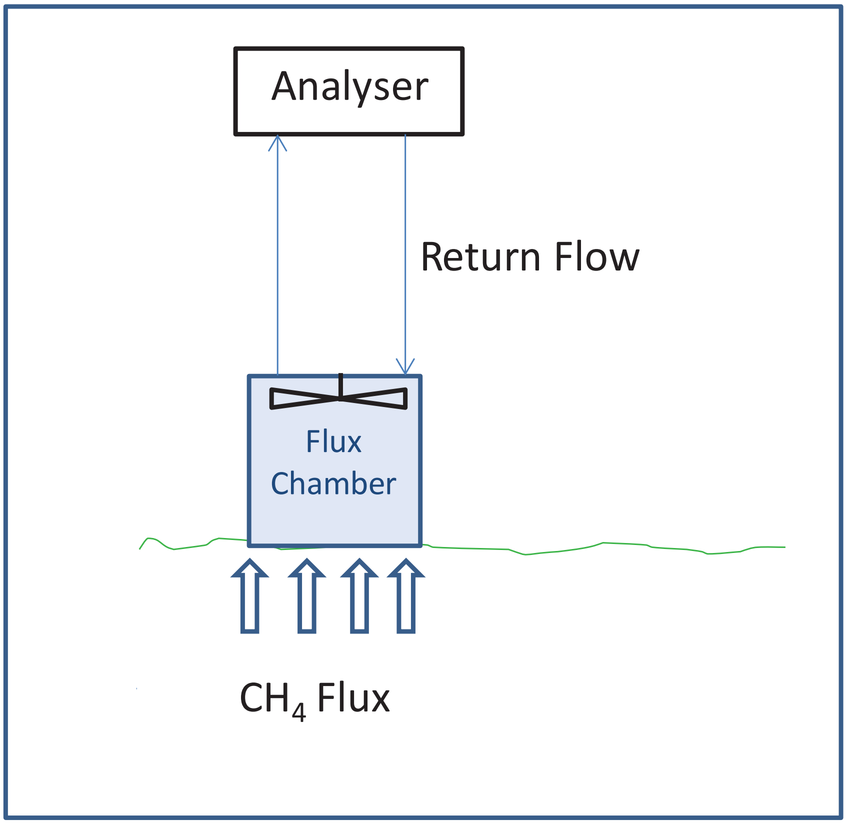

Figure 3.6. Schematic diagram of the flux chamber system used for well casing leak determinations

Typically, chamber measurements were made at four or more points within about 1 m of the well casing. In many cases, the chamber was placed adjacent to the casing, depending on access. Occasionally, additional measurements were made at distances up to about 20 m from the well head.

4 Results

4.1 Controlled Release

Controlled release experiments were conducted on several occasions with CH_4 release rates of between 0.7 and 0.8 g min^{-1} and traversing distances between 15 and 30 m downwind of the release point. Figure 4.1 shows the results of the controlled release experiments. The black markers represent the mean value determined by the traverses while the error bars show the minimum and maximum results determined over each set of traverses. The red markers represent the actual release rate.

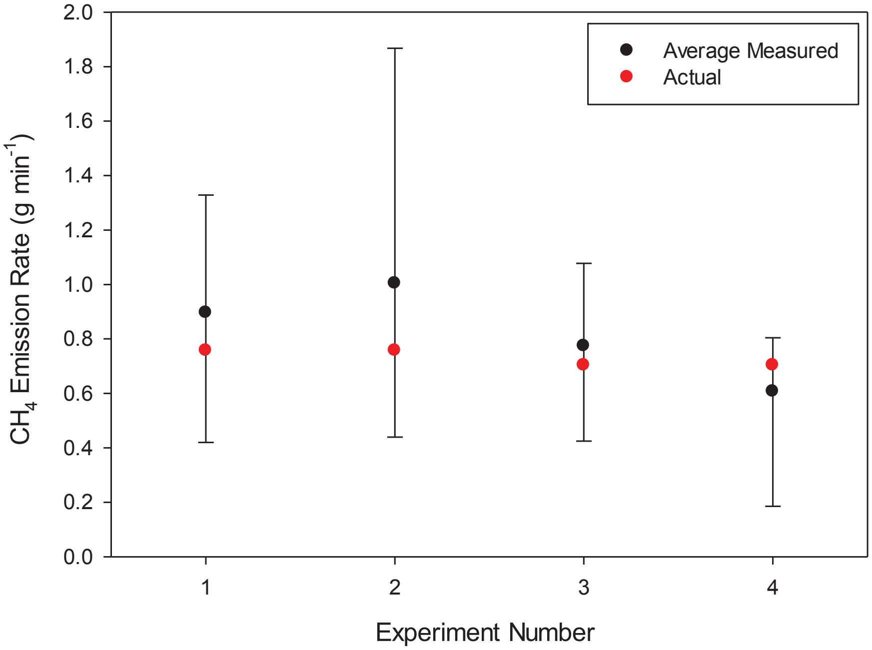

Figure 4.1. Summary of the controlled release experiments showing the CH_4 release rate determined by plume traversing and the actual release rate. Downwind distances were: Exp No 1 = 20 m; Exp No2 = 30 m; Exp No 3 = 15 m; Exp No 4 = 30 m. The error bars represent the range of emission rates measured during each set of six traverses.

Two initial experiments using a higher release rate of approximately 3.5 g min^{-1} and up to 50 m downwind overestimated the actual emission rate by about 100 and 60 % respectively. However, these experiments were based on only two traverses each so the poor agreement is unsurprising. The subsequent experiments (shown in Figure 4.1) were made using six traverses for each determination. In these cases, the agreement was much better with the emission rate determined by the average of the six runs being within about 30 % of the actual release rate, although there was significant variation among the individual traverses as shown by the error bars in Figure 4.1. Measurements made at CSG wells using the plume traversing method were therefore based on at least six and usually 10 or more individual traverses at each site.

4.2 Well Measurements

Emission measurements were made at 43 sites in NSW (six sites) and Queensland (37 sites). Most sites had only a single well on the pad, but there were a number where up to four well heads were located on an individual pad. The majority of wells were production wells, although 11 were not flowing at the time of the measurements due to maintenance or other activities. Two of the wells examined were plugged and abandoned and one well had been ‘suspended’ where the well head was still in place but had been disconnected from the gathering network and most of the surface equipment had been removed.

Twenty-nine wells were producing gas during the measurements, flowing at rates ranging from less than 1000 m^3 day^{-1} to more than 186,000 m^3 day^{-1}. Eleven of the sampled wells were hydraulically fractured. The selection also included a mix of free-flowing wells (water was not pumped from the well) and pumped wells (water was pumped from the well to allow gas flow). Pumped wells used on-site engines to power hydraulic pumps or generators to drive down-hole water pumps. In all but one case (which used diesel), these engines were fuelled from gas supplied from the well. A summary of the wells is shown in Table 4.1. To maintain commercial confidentiality, the well locations and operators of individual wells are not identified in this report.

Table 4.1. Details of wells examined during this study.

Well Number	Completion Date	Production Rate (m^3 day^{-1})	Fracture Stimulated	Type	Pump with Engine	Wells on Pad
A1	11/10/1999	1,470	Yes	Vertical	No	1
A2 - Suspended	1/05/2003	0	Yes	Vertical	No	1
A3	1/07/2007	0	Yes	Vertical	Yes – not running	1
A4	20/04/2010	18,400 (total of all 4 wells on pad)	No	Horizontal	No	4
A5	8/06/2011	14,900	No	Horizontal	Yes	2
A6	11/12/2007	13,700	No	Horizontal	No	1
B1	24/09/2006	38,880	No	Vertical	Yes	1
B2	11/01/2008	0	No	Vertical	No	1
B3	06/08/2011	9,360	No	Vertical	Yes – not running	1
B4	21/09/2010	26,400	No	Vertical	Yes – not running	1
B5	08/12/2010	0	No	Vertical	No	1
B6	27/04/2003	23,760	Yes	Vertical	Yes	1
B7	09/08/2007	26,400	No	Vertical	Yes	1
B8	26/01/2008	62,400	No	Vertical	No	1
B9	23/06/2008	7,680	No	Vertical	Yes	1
B10	07/04/2007	55,200	No	Vertical	No	1
B11	23/06/2011	94,602	No	Vertical	Yes – not running	1
B12	28/06/2011	0	No	Vertical	Yes – not running	1
B13	21/02/2005	0	No	Vertical	No	1
B14	30/08/2007	75,360	No	Vertical	No	1

B15	08/04/2009	70,800	No	Vertical	No	1
C1	15/05/2001	76,101	No	Vertical	Yes	1
C2	2/08/2003	853	No	Vertical	Yes	1
C3	4/10/2007	0	No	Vertical	Yes – not running	1
C4	29/03/2007	52,458	No	Vertical	Yes	1
C5	29/03/2007	58,594	No	Vertical	Yes – not running	1
C6	28/01/2008	186,464	No	Vertical	Yes	1
C7	17/09/2009	0	Yes	Vertical	No	1
C8	22/05/2010	0	No	Horizontal	No	2
C9	16/10/2003	78,731	Yes	Vertical	No	1
C10	1/10/2003	85,556	Yes	Vertical	No	1
C11	27/08/2004	0	Yes	Vertical	No	1
D1 - Abandoned	8/11/2003	0	No	vertical	No	1
D2	1/09/2005	93,400	Yes	vertical	No	1
D3 - Abandoned	29/11/2003	0	Yes	vertical	No	1
D4	19/04/2004	0	Yes	vertical	Yes (x2 – not running)	1
D5	7/11/2009	7,900	No	vertical	Yes (x2)	1
D6	28/11/2009	0	No	vertical	Yes (x2)	1
E1	16/3/2008	43,843 (total of both wells on pad)	No	vertical	Yes	2
E2	7/9/2008	26,847	No	vertical	Yes	1
E3	16/3/2007	3,707	No	vertical	Yes – not running	2
E4	31/5/2009	6,598	No	vertical	Yes	1
E5	31/5/2005	14,498 (total of all 3 wells on pad)	No	vertical	Yes	3

Downwind plume traverses were made at all wells sites except Wells B7 and C3 where the wind was too light to produce stable plumes. Of the well sites where traverses were made only three did not exhibit any CH_4 emissions. These were the two plugged and abandoned wells (D1 and D3) and the suspended well (A2). All of the other wells examined exhibited some level of CH_4 emissions although in most cases the amount was relatively small. The plume traversing results for all wells are presented in Table A1 in the Appendix.

On-pad measurements were made at most wells except in a few cases where high ambient CH_4 levels from major leaks or vents made locating minor leak points difficult. In one case at Well B2, CH_4 released from a vent on a water gathering line was drifting over the pad components so it was not possible to determine if there were other leaks against the high background. Similar conditions were encountered at Wells C3 and E4 where variable plumes from leaks around the water pump shaft seals precluded reliable leak detection. In one case we attempted to measure emissions from a well about 500 m downwind of a gas compression plant but the CH_4 emissions from the plant prevented any measurements being made at this site.

Most of the CH_4 emissions were found to be derived from equipment leaks and venting but we also found that exhaust from the engines used to drive the water pumps on some wells was frequently a significant source of methane. Fifteen of the pumped wells had the engines operating during the measurements and in most cases the exhaust was found to contain CH_4 that contributed to total emissions. In a few cases, the plume from the engine exhaust was sufficiently spatially separated from other sources of CH_4 to quantify the sources separately using the traverse method (Figure 4.2).

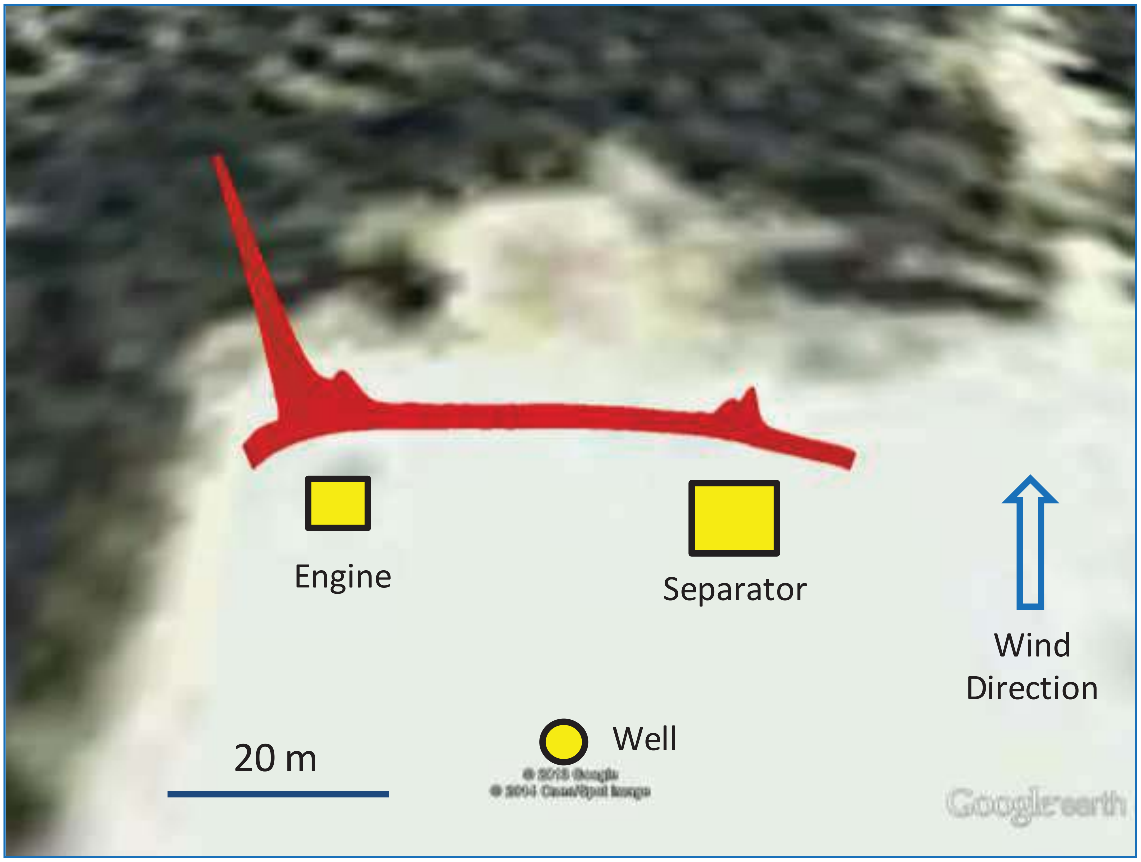

Figure 4.2. Methane concentration profile at Well C2 showing the separate plumes associated with the engine and equipment leaks elsewhere on the pad.

However, in most cases the plumes were coincident and the exhaust component could not be separated. To attempt to estimate the magnitude of engine emissions, we measured the CH_4 concentration in the exhaust outlet of the engine where this was possible. The range of CH_4 concentration varied considerably; from only a few ppm to more than 1500 ppm. The exhaust gas flow rate was estimated from the nominal fuel consumption (often stated on the engine nameplate) or power rating and assuming a 33 % efficiency and 17:1 air fuel ratio.

In the example for Well C2 shown in Figure 4.2, the plume traverse yielded an emission rate from the engine of 0.8 g min^{-1} compared to the estimate based on the fuel consumption and exhaust CH_4 concentration of 0.9 g min^{-1}. In another example, engine emissions from Well B7 were estimated using the exhaust method to be 0.2 g min^{-1}. A separate measurement made by the well operator using a stack testing method also gave 0.2 g min^{-1}. While these two examples suggest that this method provides a reasonable approximation of exhaust CH_4 emissions, in many cases the CH_4 concentration measured was well above the calibrated range of the CH_4 analyser (i.e. > 280 ppm) and hence the results can only be considered indicative.

Although on-pad measurements provided reasonably accurate leak rate results for individual leak points, the large number of possible emission sources including equipment leaks, vents, pneumatic devices and engine exhaust presented a risk that some emission points on each pad would be missed during the surveys (Figure 4.3).

Figure 4.3. CSG well pad showing some of the surface equipment and potential emission points. Note the engine in the background for supplying hydraulic power to the water pump.

To check this we compared the emission rates determined from the on-pad measurements to those calculated from the downwind traverses, which capture all emissions from the pad. Ideally therefore, if all the emission sources have been accounted for, on-pad measurements should equal emission rates determined from traverse data. Apart from one result, there was generally good agreement between the two methods, which is shown in Figure 4.4 where the emission rate determined for each well by the on-pad methods is plotted as a function of the traversing results. The outlier (red marker in Figure 4.4) corresponds to Well B2 where the traverses were made under very light and variable conditions, which make accurate quantification difficult. The mean traverse result for this well was approximately 17 g min^{-1} but this result exhibited the greatest variably of all the traverses, ranging from 1 to 66 g min^{-1}. If this result is omitted from the plot, the slope of the line is close to 1 (0.94) confirming that the on-pad measurements generally accounted for the main emission points i.e. there were no major sources that were missed during the leaks surveys.

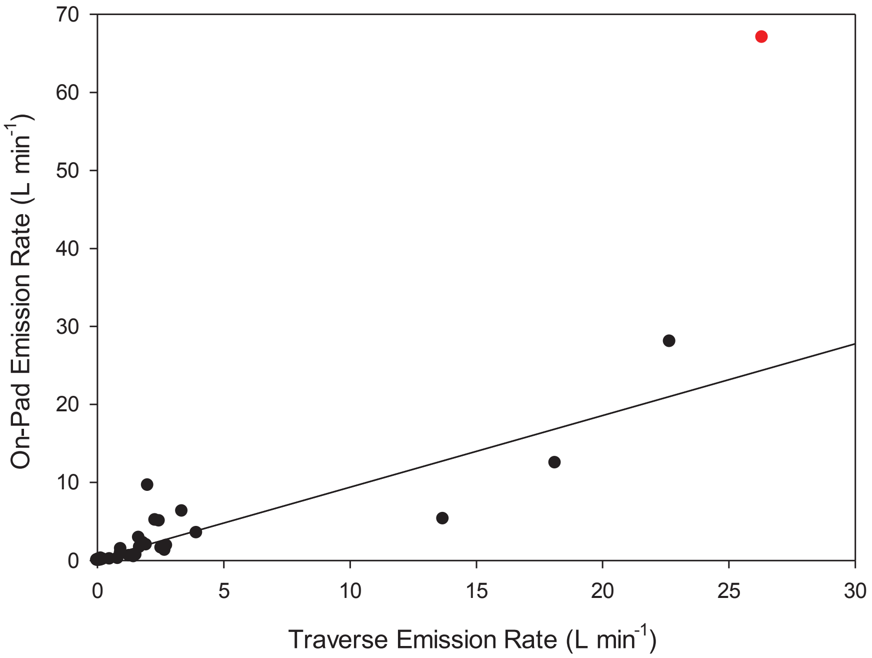

Figure 4.4. Correlation of total CH_4 emissions determined by traverses with on-pad measurements

The well site results from individual companies are discussed in more detail in the following sections.

4.2.1 COMPANY A

Figure 4.5 summarises the total emissions measured at Company A's well sites using the traversing method. At the time of the measurements only four wells were producing gas – Well A2 was suspended and Well A3 was shut-in for maintenance.

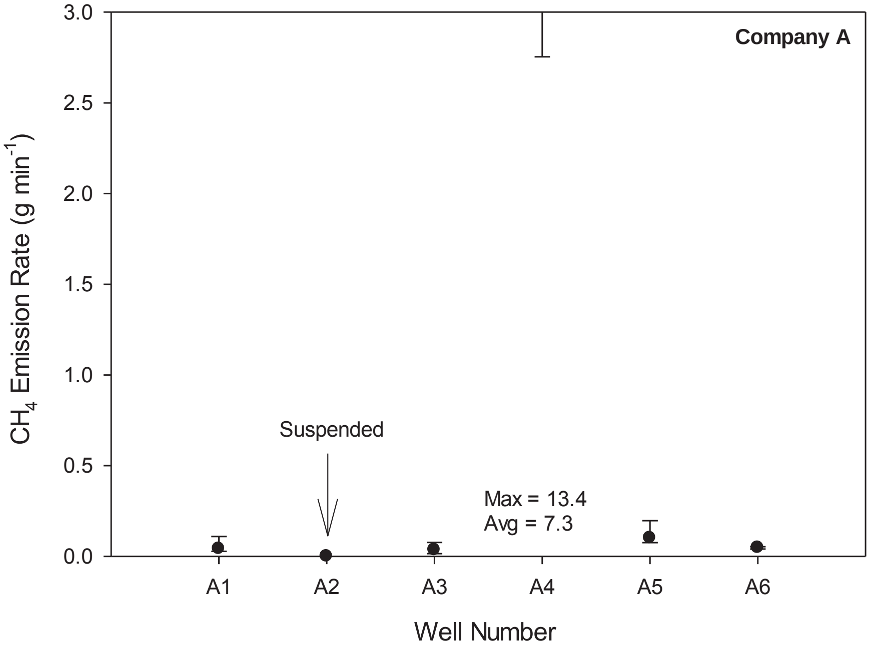

Figure 4.5. Total CH_4 emission rates estimated at Company A's well sites using the traversing method.

Apart from the suspended well (A2) emissions were detected at each site. Generally emissions were very low rwith five of the wells having emissions below about 0.1 g min^{-1}. On-pad measurements made at the well sites showed that in two cases (Wells A1 and A5) the emissions were due to the operation of pneumatic devices with emission rates of ~75 mg min^{-1} and 55 mg min^{-1}, respectively.

Two other wells (A3 and A6) were also found to have minor emissions but at the time the measurements were made, venting from pneumatic equipment was not contributing (i.e. these devices did not operate over the few hours we were on site at each well). In the case of A6, CH_4 was leaking slowly from a loose plug on a branch pipe at a rate of 22 mg min^{-1}. This leak was repaired by gas company personnel shortly after it was identified and further measurements on site showed that the leak had been eliminated. At Well A3, a leak was found in the gathering line, but again, this was very small amounting to less than 1 mg min^{-1}.

The largest emissions were found at Well A4. Two separate sets of traverses yielded an average emission rate of 7.3 g min^{-1}. Methane leaks were detected at a valve and pipe joint on the well pad but the combined emission rate from these was about 7 mg min^{-1} so the bulk of the methane release was from another source. This well was on a pad with three other wells within close proximity, which were not examined in detail during this campaign, so it is possible that some of the observed methane in the plume may have originated from these other wells. However, the bulk of the source was traced to a buried gathering line adjacent to the pad that serviced all four wells. We attempted to measure the emission rate using the surface flux chamber method; however, because of the diffuse nature of the emissions through the gravel, this was not successful.

Although the average emission rate of 7.3 g min^{-1} (15.5 m^3 day^{-1} at 15 °C) determined by the traverses was by far the largest emission source found at Company A, it represented only about 0.1 % of the indicated gas flow of 18,400 m^3 day^{-1} from the four wells on the pad.

A summary of the emissions determined by on-pad measurements at Company A is provided in Table 4.2.

Table 4.2. Summary of on-pad emission rates measured at Company A sites; nf denotes 'not found'. Note the leak rate shown for Well A6 was determined from the traverses.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
A1	3.3×10^{-4}	nf	7.5×10^{-2}
A2	0	nf	nf
A3	4.5×10^{-4}	nf	nf
A4	7.3	nf	nf
A5	0	nf	5.5×10^{-2}
A6	2.2×10^{-2}	nf	nf

4.2.2 COMPANY B

Methane emissions estimates based on the traverses for the Company B wells are summarised in Figure 4.6.

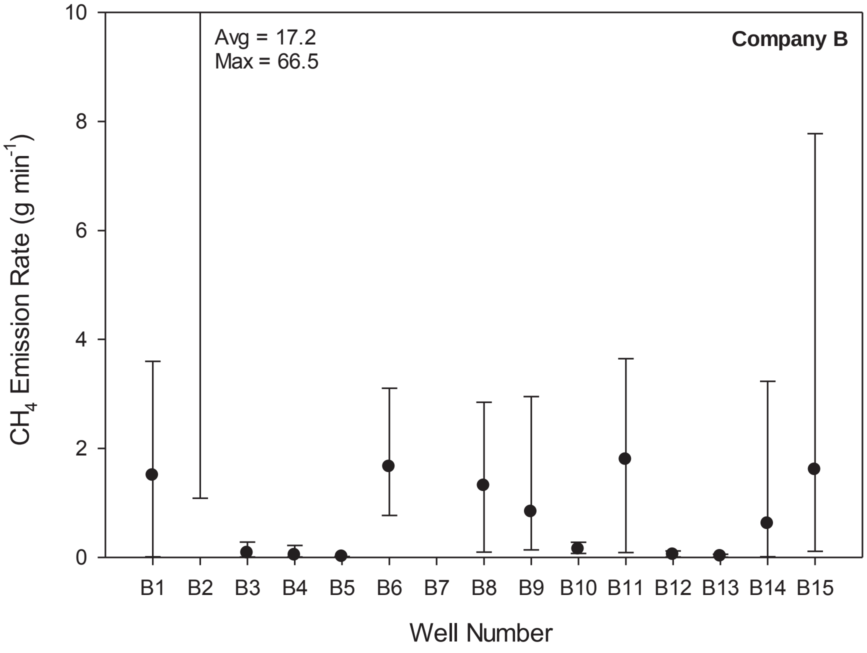

Figure 4.6. Total CH_4 emission rates estimated at Company B's well sites using the traversing method.

These emissions were somewhat higher than measured at Company A with average emissions ranging from less than 50 mg min^{-1}, (B4, B5, B12 and B13) to 17 g min^{-1} (B2). Note however, that one individual traverse on B2 indicated an emission rate of more than 66 g min^{-1}. The traverses at Well B2 were made under light and variable wind conditions so the results are subject to high uncertainty. More accurate emissions measurements of emissions were made at B2 using an on-pad method. In this case, CH_4 was found to be predominantly released from a single vent on a water gathering pipe from the well. The flow rate from the vent was relatively constant at 44 g min^{-1} (measured using a flow calibrator), which was within the range of the traverses but higher than the traverse average of 17 g min^{-1}. The high CH_4 emission rate however, meant that it was not possible to identify any other sources on the pad because the plume was engulfing the surface equipment.

Well B2 was not flowing at the time of the measurements, but assuming the normal flow rate is 26,400 m^3 day^{-1} (i.e. the median production rate of the Company B wells examined), fugitive emissions from this vent represent about 0.4 % of the well's production.

Emissions at the other Company B well sites were much lower than B2, with emission rates generally less than 2 g min^{-1}. Most of the well sites exhibited a small level of leakage from certain items of equipment and especially a particular brand of pressure regulator. These regulator leaks however, were quite low with the maximum measured less than 25 mg min^{-1}. Most of the CH_4 emissions were, like Well B2, from vents present on many of this company's wells. Vent emissions were significantly higher than the equipment leaks, typically more than 1 g min^{-1}, with the maximum of 44 g min^{-1}.

The on-pad measurements for Company B are summarised in Table 4.3.

Table 4.3.Summary of on-pad emission rates measured at Company B sites; nf denotes 'not found'.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
B1	2.4×10^{-3}	2.9	nf
B2	nf	43.8	nf
B3	2.1×10^{-4}	nf	nf
B4	1.5×10^{-3}	nf	nf
B5	nf	nf	nf
B6	6.4×10^{-3}	1.0	nf
B7	9.6×10^{-4}	1.1	nf
B8	2.1×10^{-2}	6.2	nf
B9	2.4×10^{-3}	nf	nf
B10	2.3×10^{-2}	3.6×10^{-2}	nf
B11	2.5×10^{-2}	1.2	nf
B12	3.0×10^{-4}		nf
B13	1.0×10^{-3}	$< 10^{-4}$	nf
B14	3.94×10^{-3}	0.9	nf
B15	2.4×10^{-3}	3.3	nf

In addition to the emissions from the well pads, we found a significant CH_4 emission point from a water gathering line installation near Well B13 (Figure 4.7).

Figure 4.7. Methane emission sources on a water gathering line.

Methane was being released from the two vents shown in Figure 4.7 at a rate sufficient to be audible a considerable distance from the vents. It was not possible at the time to the site visit to directly measure the emission rate from the vents due to restricted access, however, the CH_4 concentration 3 m downwind of the vents was 15 % of the lower explosive limit of CH_4 (i.e. 7,500 ppm). Based on the prevailing wind speed, we estimate that the CH_4 emission rate from the two vents was at least 200 L min^{-1} (130 g min^{-1}) or almost 300 m^3 day^{-1}. This is a factor of three more than the highest emitting well examined during this study.

4.2.3 COMPANY C

Figure 4.8 summarises the CH_4 emission rates estimated by the traversing method for Company C. Emissions were generally estimated to be below 1.5 g min^{-1}, except for Wells C1 and C4, with emission rates of about 8.7 and 11.8 g min^{-1}, respectively. The bulk of the emissions from wells C1 and C4 were due to CH_4 in the engine exhaust rather than venting or equipment leaks. Similarly, emissions from Wells C2 and C6 comprised mainly CH_4 in engine exhaust although the emissions rates were much lower than C1 and C4. On-pad measurements at each of the wells showed that emissions from the wells were generally relatively low when the engine exhaust is excluded (Table 4.4). In this case, leaks were mostly less than 0.3 g min^{-1}. Most of these leaks were found to be from vent pipes on equipment such as pressure relief valves or pressure regulators similar to those on Company B's well sites. In one case (Well C10), a pneumatic device was found to be venting at an average rate of 0.5 g min^{-1} in addition to the equipment leak rate of 0.3 g min^{-1} to give a total emission of 0.8 g min^{-1}.

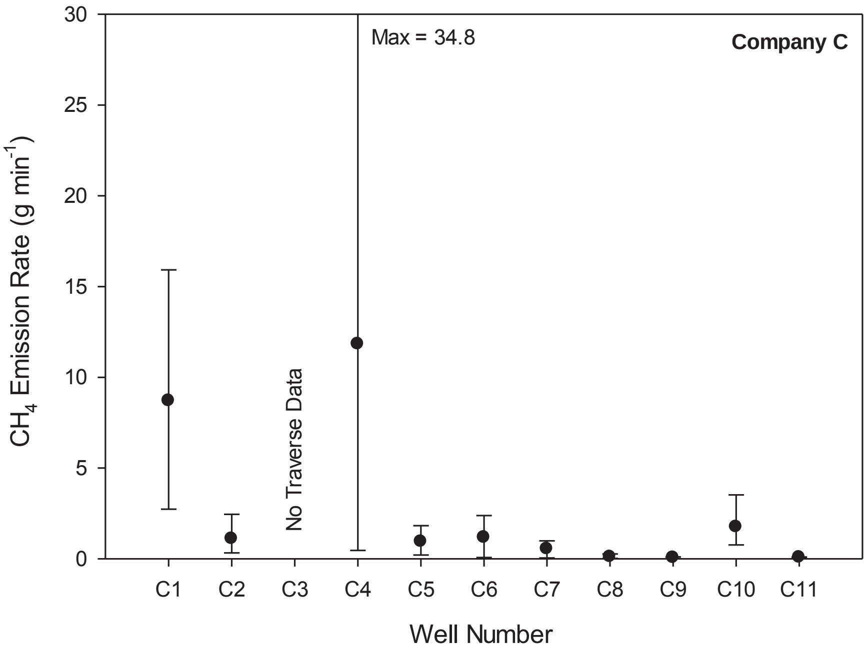

Figure 4.8. Total CH_4 emission rates estimated at Company C's well sites using the traversing method.

Traverses were not made at Well C3 due to lack of wind, however, on-pad inspections revealed a significant gas leak was on the seal of the water pump shaft. The emission rate from this leak was approximately 28 g min^{-1} (measured using the high-flow apparatus), which was the second largest well emission (after B2) and the largest equipment leak of the 43 sites examined. Since this well was shut-in at the time of measurement, it was not flowing but using the median flow rate of Company C's wells (52,500 m^3 day^{-1}) the leak rate corresponds to about 0.1 % of the well's production.

The water pump shaft seal was also found to be the source of CH_4 leakage at Well C5 but in that case, the emission rate was about 0.3 g min^{-1}, about 100 times less than C3.

Table 4.4. Summary of on-pad emission rates measured at Company C sites; nf denotes 'not found'.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
C1	5.3×10^{-2}	nf	nf
C2	0.2	nf	nf
C3	28.	nf	nf
C4	8.0×10^{-2}	nf	nf
C5	0.3	nf	nf
C6	0.2	nf	nf
C7	0.1	nf	nf
C8	2.1×10^{-3}	nf	nf
C9	8.9×10^{-3}	nf	nf

C10	0.3	nf	0.5
C11	7.4×10^{-2}	nf	nf

4.2.4 COMPANY D

Two of the wells at Company D were plugged and abandoned with all surface equipment removed. Detailed traverses and flux chamber measurements made on the well sites revealed no sign of any residual emissions from these wells. The traversing results for Company D are shown in Figure 5.9.

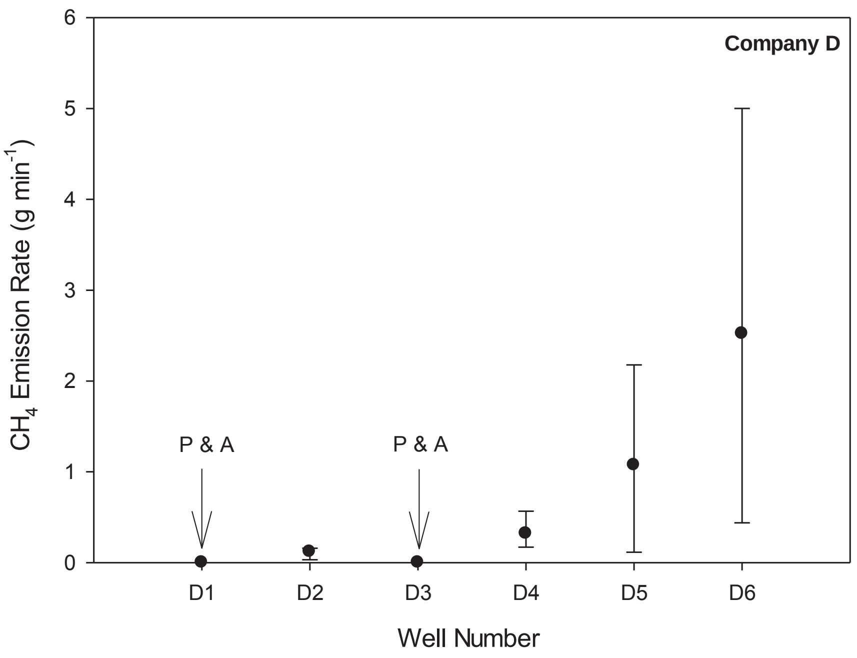

Figure 4.9. Total CH_4 emission rates estimated at Company D's well sites using the traversing method.

Of the operating wells, D2 had the lowest emissions with on-pad measurements indicating total emissions of less than 60 mg min^{-1}, which were due to minor equipment leaks. Well D4 also had low emissions totalling about 65 mg min^{-1}. A small emission from a pneumatic actuator of approximately 14 mg min^{-1} was also found on well D4.

Wells D5 and D6 had higher total CH_4 emission rates and although affected by engine exhaust, significant proportions of the observed emissions were due to equipment leaks. In the case of D5, most of the CH_4 was leaking from the water pump shaft seal at about 1.5 g min^{-1} (Table 5.5). For D6, we estimate that about two thirds of the CH_4 was due to engine exhaust but approximately 0.75 g min^{-1} was leaking from what appeared to be a damaged diaphragm in a valve actuator (Figure 5.10). Several smaller leaks on this well resulted in a total leak rate of about 0.9 g min^{-1}.

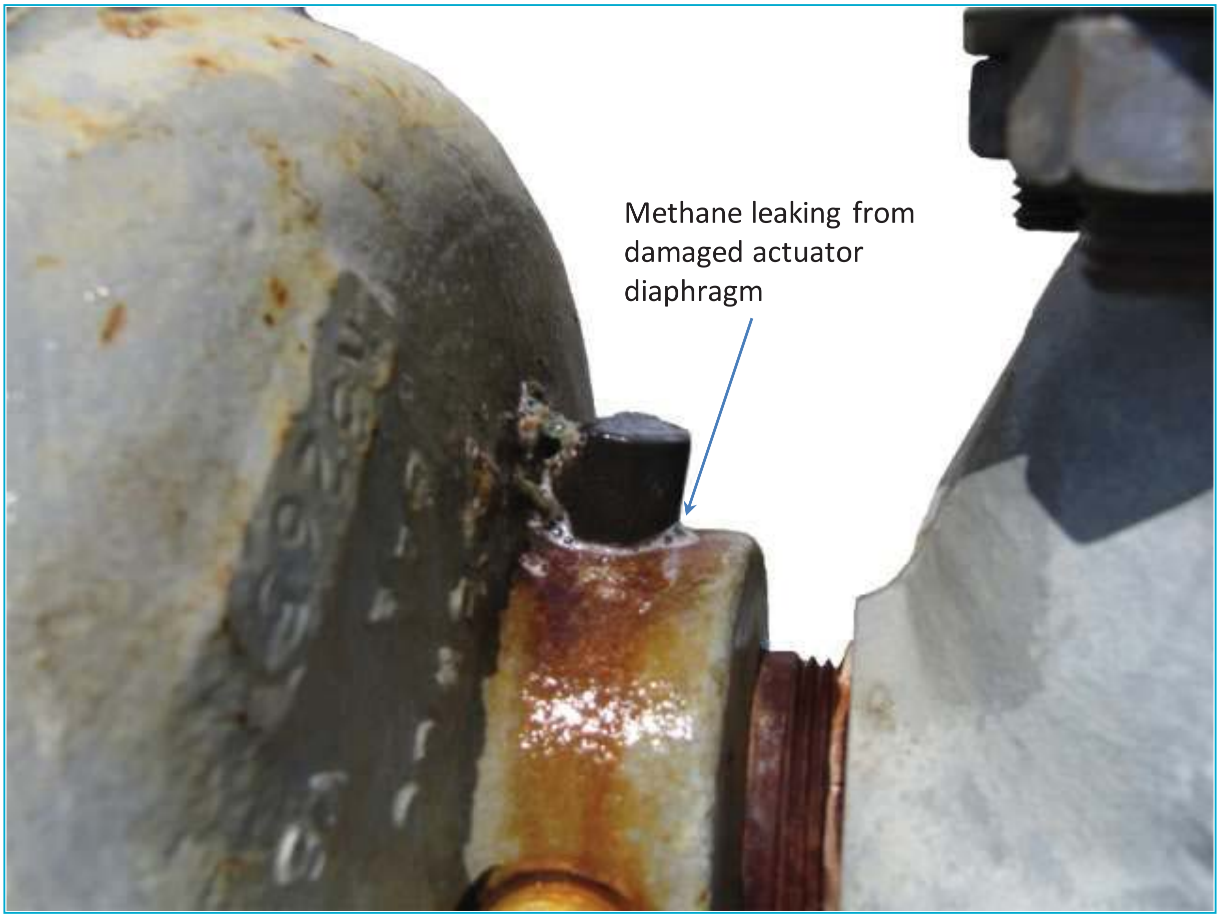

Figure 4.10. Methane leak from a valve actuator. Note the soap solution bubbles around the emission point.

Table 4.5 shows a summary of the on-pad results from Company D.

Table 4.5. Summary of on-pad emission rates measured at Company D sites; nf denotes 'not found'.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
D1	0	nf	nf
D2	5.7×10^{-2}	nf	nf
D3	0	nf	nf
D4	6.4×10^{-2}	nf	1.4×10^{-2}
D5	1.5	nf	nf
D6	0.9	nf	See note

Note: Although the emissions from the actuator shown in Figure 4.10 were from a pneumatic device, it appeared that this was due to a leak rather than normal operational emissions. Hence we have classified this as a leak in Table 4.5

4.2.5 COMPANY E

The traverse results obtained for Company E are shown in Figure 4.11. The lowest emitting well of the five examined was E5. This well was located on a pad of three wells, with a single engine providing power to all three water pumps. Emissions from all three wells were less than 60 mg min^{-1}, most of which were probably associated with engine exhaust. We did not find any equipment leaks or venting emissions at this site.

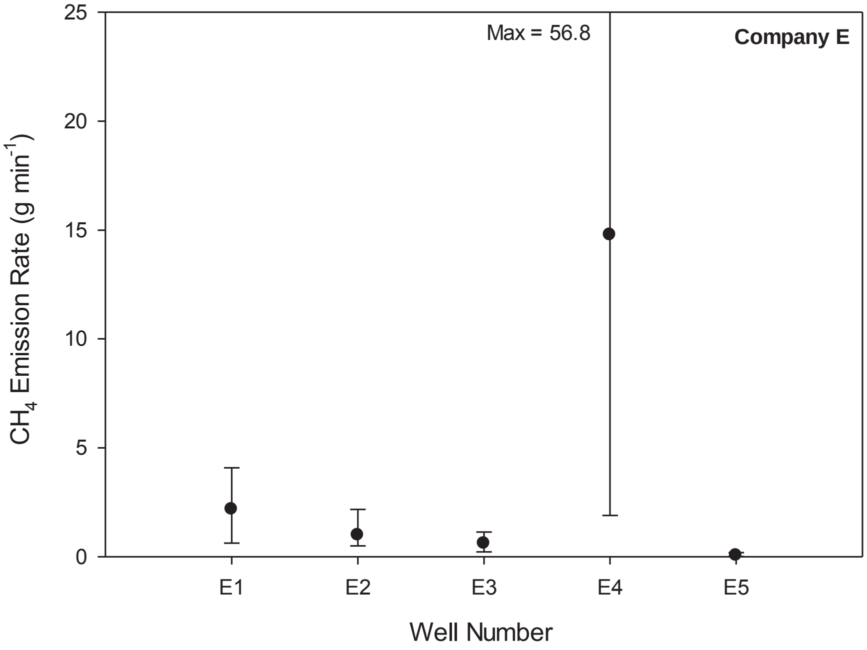

Figure 4.11. . Total CH_4 emission rates estimated at Company E's well sites using the traversing method.

The other wells, however, showed higher emissions, the largest of which was on Well E4 with an emission rate of about 15 g min^{-1}. This was traced to a leak on the water pump shaft seal. Like a number of other well sites examined during this study, the seal was repaired on site once the leak had been identified and subsequent measurements confirmed that CH_4 leakage was completely eliminated.

Well site E1 was also found to be leaking CH_4 from the water pump shaft seal. This site had two wells on the pad and both were found to be leaking from the seal. The combined rate of leak from this source was 0.7 g min^{-1}. These wells also showed significant leakage from two pressure regulators, similar to those used at various other well pads examined, with a combined emission rate of 1.7 g min^{-1}. Total emissions from leaks at E1 were 2.5 g min^{-1} (Table 4.6).

The next highest emitting well from Company E was E2 but most of these emissions were apparently from the engine exhaust. For E3, a very slight leak was detected from the pump shaft seal (about 40 mg min^{-1}) but most of the CH_4 emissions were from a leak in a filter attached to the engine fuel line (0.6 g min^{-1}).

Table 4.6. Summary of on-pad emission rates measured at Company E sites; nf denotes 'not found'.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
E1	2.5	nf	nf
E2	nf	nf	nf
E3	0.6	nf	nf
E4	15	nf	nf
E5	0	nf	nf

4.3 Casing Leaks

CSG wells are designed so that gas is extracted from the seam through a well casing but if the casing is damaged or improperly sealed into the surrounding strata, it is possible that gas can migrate to the surface outside the casing (Figure 4.12). To determine if CH_4 was escaping from the well casing, the flux chamber method was applied at each well site to measure the emission rate of any leakage from around the outside of the casing.

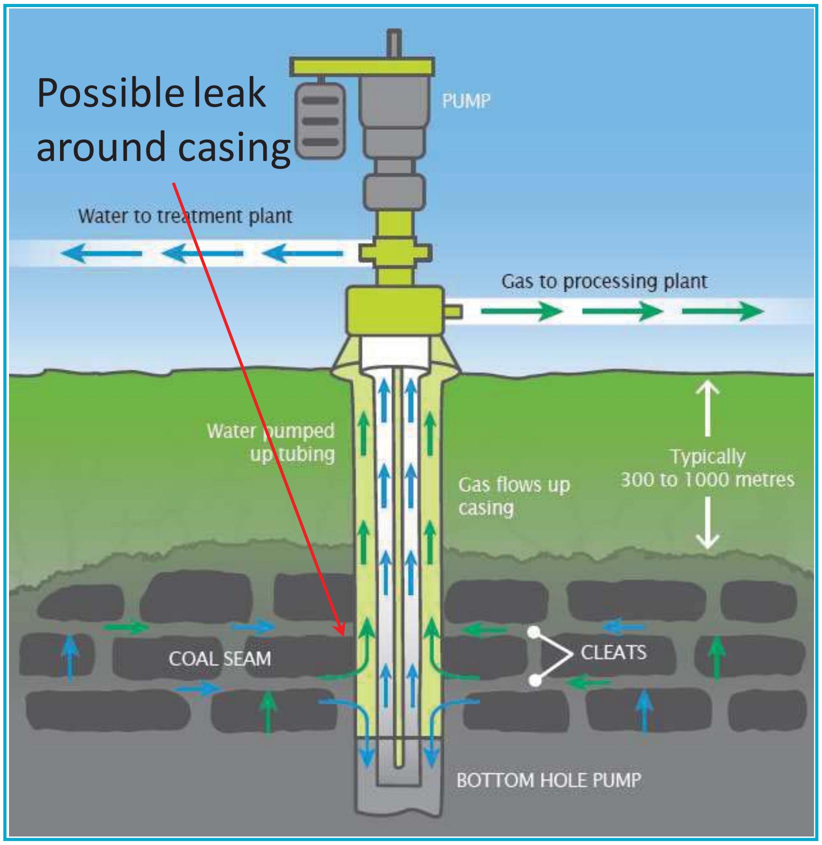

Figure 4.12. Schematic representation of a CSG well showing a possible route for CH_4 leaking outside a casing.

We anticipated that leakage from this source may be quite low, so it was important to ensure that the measurement technique had sufficient sensitivity to detect low level seepage. Therefore, prior to making field measurements a series of preliminary experiments were performed to determine the lower limit of detection of the method. Several experiments were made using a controlled release of CH_4 into the flux chamber system. Figure 4.13 (a) shows a plot of the CH_4 concentration within the chamber over about 5 minutes. The actual flow rate of CH_4 into the chamber was 7.76×10^{-5} g min^{-1} whereas the measured rate was 7.42×10^{-5} L min^{-1} or a difference of about 4 %. While this is a very low emission rate (cf. the smallest well leak rates of ~3×10^{-4} g min^{-1}) the ultimate sensitivity was several orders of magnitude lower. Measurement of CH_4 emissions from natural surfaces showed that emission rates less than 1×10^{-7} g min^{-1} could be reliably quantified (Figure 4.13 b).

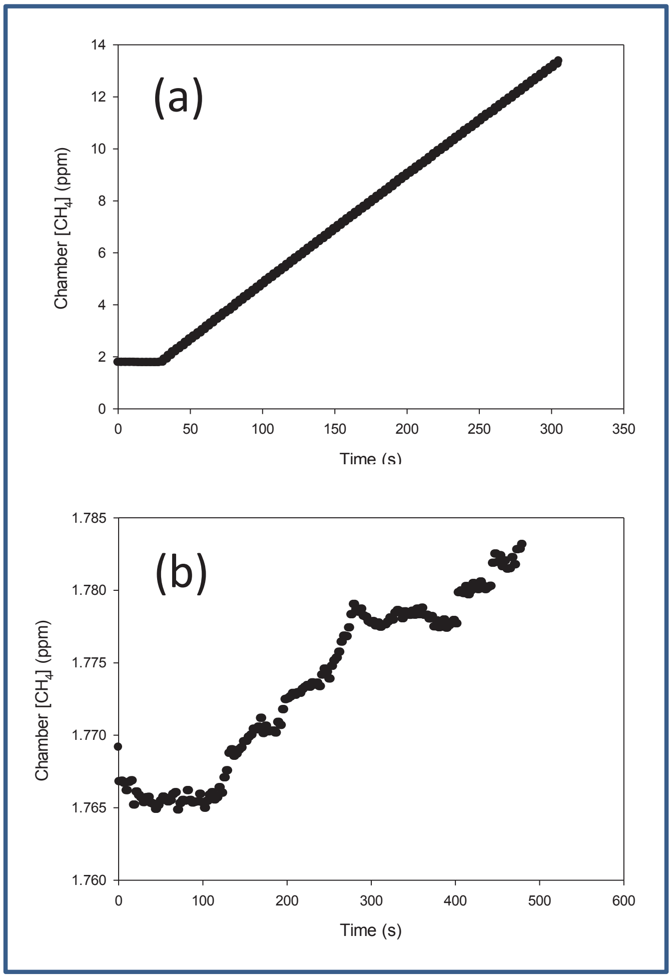

Figure 4.13. Methane concentration as a function of time in the flux chambers (a) controlled release experiment; (b) natural surface emission.

At the well sites, even with the very high sensitivity of the chamber method, we did not detect any emissions from around the well casing. Because the flux chamber measurements were applied at discreet points around the well it is possible that leak points were missed, however we believe that this was very unlikely since any significant emissions would have been detected during the mobile plume traverses and leak detection measurements made near the well heads.

5 Discussion

Overall, the emission rates measured at the well sites were quite low, especially when compared to the volume of gas produced. Of the 43 sites examined, 19 had emission rates less than 0.5 g min^{-1} and 37 less than 3 g min^{-1}; however, there were a number of wells with substantially higher emission rates up to 44 g min^{-1} (Figure 5.1).

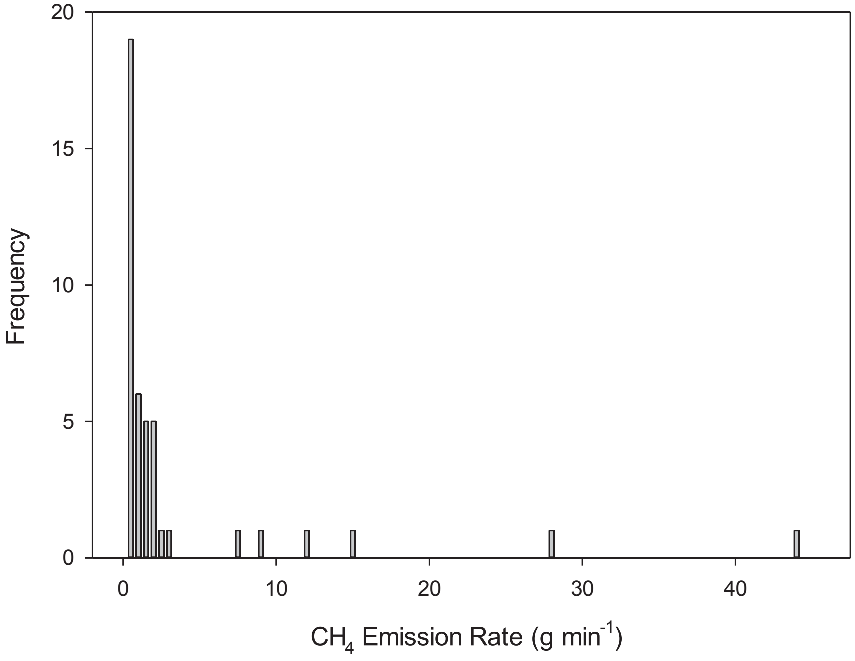

Figure 5.1. Histogram of emission rates from all sources measured at the 43 well sites.

Well pad emissions were found to be derived from several sources:

- exhaust from engines used to power dewatering pumps,
- vents and the operation of pneumatic devices and
- equipment leaks.

The mean emission rate of all of these sources for all wells is 3.2 g min^{-1} whereas the median (middle value) is 0.6 g min^{-1}.

Engine exhaust is not considered to be a fugitive emission for the purposes of greenhouse accounting since it is counted separately as a combustion source. Nevertheless, exhaust represented a significant proportion of the total CH_4 emissions at some well sites. The wide range of CH_4 concentrations present in the exhaust meant that the contribution of exhaust to overall emissions was highly variable. Some engines appear to have very low CH_4 emissions such as that at Well A5. Similarly, an unidentified well in Queensland was found to have no detectable CH_4 in the exhaust within close proximity to the pad (Day et al., 2013). On the other hand, engine exhaust was by far the primary source of CH_4 emissions at some wells (e.g. Wells C1 and C4).

As noted in Section 2, methane emissions from combustion are estimated for NGER reporting using an emission factor of 0.1 kg CO_2-e GJ^{-1} (DIICCSRTE, 2013b), which is equivalent to 4.8 g CH_4 GJ^{-1} using a global warming potential for CH_4 of 21. Assuming that the fuel consumption of the well site engines was 594 MJ

h^{-1} (indicated on the nameplate fitted to one make of engine commonly used throughout the industry), this equates to a CH_4 emission rate of 0.05 g min^{-1}, which lower than some of the estimates made during the study. Well C4 for example was estimated to be emitting CH_4 at a rate of 11.8 g min^{-1}.

Pneumatic devices, which are potential emission points, were installed at many wells, although during the measurement campaign, only seven of these were releasing CH_4 at the time of the site visits. Emissions from the these pneumatic devices ranged from 3.8×10^{-2} to 0.47 g min^{-1} with a mean emission rate 0.12 g min^{-1} and standard deviation of 0.18 g min^{-1}. This is somewhat lower than the emission rate for pneumatic devices recently reported by Allen et al. (2013). They found that the average emission rate from intermittent pneumatic devices at U.S. unconventional gas well was 5.9 ± 2.4 g min^{-1}. The result obtained for the Australian CSG wells is also lower than the production average emission factor for pneumatic devices provided in the API Compendium (API, 2009) of 345 ± 49.5 scf d^{-1} (4.6 ± 0.66 g min^{-1}).

It is not clear why these emission rates are lower than the U.S. estimates; however, it should be borne in mind that the results of our study represent only a very small sample. The Allen et al. (2013) study examined 305 devices compared to only seven in our study. Another reason for the difference may be due to the intermittent operation of the devices. Most of the CH_4 emission apparently occurs when the devices operate and hence the frequency of operation has a strong influence on the emission rate so a longer period of sampling may have yielded different results.

Despite the uncertainty of the results for pneumatic devices, it is probable that emissions from these systems will tend to decrease in the future. Some Australian CSG companies are now installing compressed air operated or electrical actuators on newer well pads which will eliminate pneumatic CH_4 emissions from these pads.

Vents installed at various points on some well pad equipment were frequently found to be sources of CH_4 emissions. Of the 43 well sites examined, ten had vents, all from Company B, that were emitting CH_4 at the time measurements were made. The rate of emissions varied substantially from less than 10^{-4} g min^{-1} up to 44 g min^{-1}, which was the highest rate of emissions measured from any source measured during this project. The mean vent emission rate was 6.1 g min^{-1} with a standard deviation of 13.4 g min^{-1}, reflecting the large range of values.

The third main source of well pad CH_4 emissions was from equipment leaks. Most of the wells examined were found to have some degree of leakage from equipment on the pad. Minor leaks (usually less than 60 mg min^{-1}) were found on various items such as fuel lines to engines, valves, sight gauges on separators and other equipment. However, there were some leak points that were consistently found across the well sites. The first of these was a particular type of pressure regulator installed at many wells (Figure 5.2). This device was apparently associated with the separator and was usually found to be leaking a small amount of CH_4. Mostly, these leaks were less than 150 mg min^{-1} but in one case (Well E1) the emission rate was about 1.5 g min^{-1}.

Figure 5.2. Pressure regular that was a common source of CH_4 leakage.

The other common leak point was the seal around water pump shafts on pumped wells (Figure 5.3). The two largest equipment leaks detected were due to leaking seals at Wells C3 and E4. At the time of the site visit, Well C3 was shut-in for maintenance and as a result the pressure on the seal was almost 2 MPa, which was much higher than normal operating pressure and this is likely to have contributed to the high leak rate from the well. This is consistent with a study of leaking wells in Queensland made in 2010 where high CH_4 concentrations (up to 6 % CH_4) due to leaks were often found on shut-in wells that were under high pressure (DEEDI, 2010).

Figure 5.3. Well head showing the location of the water pump shaft and seal which was found to be a common leak point.

At Well E4, the seal had apparently 'dried out' since the previous inspection and was allowing CH_4 to leak around the rotating pump shaft at almost 15 g min^{-1}. After the leak was identified, however, maintenance staff applied more grease to the seal and tightened the gland around the shaft, which effectively eliminated the leak. A smaller leak of around 1.5 g min^{-1} on the shaft seal on Well D5 was also repaired on site by simply tightening the gland.

Although the water pump shaft seal is a potentially large source of CH_4 emissions, it is clear that in many cases these leaks can be easily repaired. Regular inspection of these seals, especially during shut-ins when the well pressure may increase substantially, is therefore likely to be important for minimising well site emissions.

None of the wells examined during this study exhibited any sign of CH_4 emissions around the well casing so this does not appear to be a common route for CH_4 release. Methane leaks have been detected at ground level adjacent to well casings on Australian CSG wells previously but these were traced to leaks in the threaded connection between the casing and well head base (DEEDI, 2010) rather than gas leaking around the outside of the casing.

Despite this, it has been suggested that 6 to 7 % of well completions in the United States are subject to integrity failure that could lead to CH_4 leakage (Ingraffea, 2013). Given that we surveyed less than 1 % of

Australian CSG wells, it is possible that the small sample size is not sufficiently representative to assess the true extent of well leakage. Further work would be required to conclusively determine the extent of casing leaks.

Four of the wells surveyed were horizontal; the remainder were vertical. The range of emissions from the four horizontal wells was 0.05 to 7.3 g min^{-1} compared to 0 to 44 g min^{-1} for the vertical wells. It is not possible based on only four wells to determine if horizontal wells have different emission characteristics compared to vertical; however, it seems unlikely that this would be the case. The emission routes were always associated with surface equipment, some of which was common to both horizontal and vertical well pads.

Eleven wells examined had been hydraulically fractured and as shown in Table 5.1, average emissions from these wells were lower (0.42 g min^{-1}) than those measured on the unfractured wells (4.2 g min^{-1}). Because the data are heavily skewed and it is unlikely that the sample size is statistically representative, it is misleading to draw conclusions about the relative emission rates based on a comparison of means alone. Methane emissions were observed from both fracture stimulated and unfractured wells but in all cases, emissions were from surface equipment that would not be expected to be affected by the stimulation method. Therefore, the observed difference between the emission rates of the fractured and unfractured wells in this sample is probably unrelated to the stimulation method.

Table 5.1. Comparison of emission rates measured on hydraulically fractured and unfractured wells.

	Fractured	Unfractured
Number of Wells	11	32
Mean (g min^{-1})	0.42	4.2
Median (g min^{-1})	0.07	1.0
Std Deviation (g min^{-1})	0.66	14.3

Another parameter that was initially thought to possibly contribute to differences in emission rates was the well production rate. The range of gas production from the wells varied substantially but there was no observable correlation between production and leak rate. The highest emissions were from wells that were not producing gas at the time of the measurements. In the case of one of the non flowing wells (C3) at least, it may have been that the high well pressure due to the shut-in was contributing to the high leakage. Conversely, Well C6, which was producing about 186,000 m^3 day^{-1} (cf. the median production rate of 13,700 m^3 day^{-1}) had relatively low emissions, most of which were derived from the exhaust from the engine on the well pad.

Despite the rather low well pad emissions measured during this study, a much higher emission source was identified on a water gathering line installation. Unfortunately accurate measurements could not be made at this site but indicative estimates suggested that the emission rate from this source was at least three times higher than the largest emission rate measured on any of the wells. Similar installations are widespread through the Queensland gas regions and occasionally, gas can be heard escaping from vents on these systems. It is possible that these may be a significant source of CH_4 and is an area that needs further investigation.

5.1 Emission Factors

As discussed in Section2 emissions from equipment leaks are often estimated for NGER reporting according to Method 1 using a generic emission factor of 1.2 kg CO_2-e t^{-1}, which is equivalent to 57 g CH_4 t^{-1}. It is therefore instructive to compare this emission factor to the leak emission data measured in the field. The field measurements yielded a median leak rate 0.02 g min^{-1} and mean rate of 1.6 g min^{-1} from the 35 wells where leaks were found. The median production rate of the wells was 13,700 m^3 day^{-1} or 9.3 t CH_4 day^{-1} (referenced to 15 °C). Dividing the median daily leak rate by the median production rate gives an emission factor of approximately 4 g CH_4 t^{-1} or 0.1 kg CO_2-e t^{-1} (based on a global warming potential of 21). Using the mean leak rate of 1.6 g min^{-1} and mean production rate of 29,600 m^3 day^{-1} yields an emission factor of 115 g CH_4 t^{-1} or 2.4 kg CO_2-e t^{-1}. This range is consistent with the current NGER emission factor for general equipment leaks and tends to confirm that equipment leaks comprise only a very small proportion of greenhouse gas emissions from CSG production.

Similar calculations may be made to develop emission factors for vents and pneumatic equipment. A summary of the emission data for leaks, vents and pneumatic equipment and the corresponding emission factors calculated from these data are shown in Table 5.2.

Table 5.2. Summary of emission data from leaks, vents and pneumatic equipment. Emissions factors calculated from the mean emission rate for each category are also shown in units of kg CO_2-e t^{-1} (GWP of 21 used in this calculation).

	Equipment Leaks	Vents	Pneumatic Equipment
Mean (g min^{-1})	1.59	6.05	0.12
Median (g min^{-1})	0.02	1.14	0.06
Std Dev	5.36	13.40	0.18
N	35	10	7
Calculated Emission Factor from Mean Emission Rate (kg CO_2-e t^{-1})	2.4	9.1	0.2

Although these averaged emission factors are low it should be remembered that firstly, the number of wells examined was less than 1 % of wells in operation so may not be representative of the total well population and secondly, there were several equipment leaks that were much higher than the average values (Figure 5.1). The maximum leak rate measured in this study was about 28 g min^{-1} on Well C3 and although this well was not flowing at the time, based on the median production rate for all wells, is equivalent to 91 kg CO_2-e t^{-1}. A high leak rate of 15 g min^{-1} was also found at Well E4 and based on its production rate, equates to 102 kg CO_2-e t^{-1}. These leak rates are about two orders of magnitude higher than the current NGER emission factor for equipment leaks.

Another important point with regard to the reliability of emission factors is that they may change due to operating conditions or maintenance. For instance, the leak from Well E4 discussed above was repaired during the site visit and completely sealed. Several other leaks were effectively repaired during the course of the visits once they were identified. However, since wells operate largely unattended, there may be some time between when the leak forms and when it is repaired.

With regard to well casing leaks there is currently no emission factor representative of Australian operations for estimating emissions. The current Method 2 emission factor is based on measurements made at some Canadian wells during the mid 1990s (CAPP, 2002). While there have been suggestions that well leakage may be a significant source of emissions (Somerville, 2012), the wells examined in this study showed no evidence of emissions via this route. But again, this needs to be considered in the context of the small number of wells examined.

6 Conclusions

Fugitive CH_4 emission rates were measured at 43 CSG well sites in Queensland and NSW. A range of methods was applied including downwind traverses of CH_4 plumes originating from well pads, and on-pad measurements to determine leak rates from individual items of equipments and well casings.

Emission rates from production sites ranged from zero to a maximum of about 44 g min^{-1}. The highest emission rate was due to CH_4 released from a vent on the well pad while the lowest emitters were two plugged and abandoned wells and a suspended well. All of the producing wells were found to have some level of emissions, although in all cases these were very low compared to overall production. Emissions were found to comprise equipment leaks, venting, pneumatic device operation and engine exhaust. The wells examined in this study did not show any evidence of CH_4 migration outside the well casing.

Overall, the median CH_4 emission rate from all sources for the wells examined was approximately 0.6 g min^{-1} while the mean emission rate was about 3.2 g min^{-1} or about 7 m^3 day^{-1}. This compares to a mean production rate of the 43 wells of 29,600 m^3 day^{-1} and represents about 0.02 % of total production. This is very much lower than recent estimates of CH_4 emissions from unconventional gas production in the United States.

Apart from vents, highest emissions were due to CH_4 leaking from seals on water pump shafts. On several occasions, these leaks were repaired on site once they were identified. The median emission rate of all the equipment leaks identified was 0.02 g min^{-1} and the mean was 1.6 g min^{-1}, which yield emission factors of about 0.1 kg CO_2-e t^{-1} and 2.4 kg CO_2-e t^{-1}, respectively. This range is consistent with the emission factor currently used in the National Energy and Greenhouse Reporting Method 1 methodology for estimating equipment leaks.

Although well pad emissions were generally found to be low, one significantly higher emission source was found on a vent associated with a water gathering line. This source appeared to be at least three times higher than the highest emission rate from any well examined.

The results obtained in this study represent the first quantitative measurements of fugitive emissions from the Australian CSG industry; however, there are a number of areas that require further investigation. Firstly, the number of wells examined was only a very small proportion of the total number of wells in operation. Moreover, many more wells are likely to be drilled over the next few years. Consequently the small sample examined during this study may not be truly representative of the total well population. It is also apparent that emissions may vary over time, for instance due to repair and maintenance activities. To fully characterise emissions, a larger sample size would be required and measurements would need to be made over an extended period to determine temporal variation.

In addition to wells, there are many other potential emission points throughout the gas production and distribution chain that were not examined in this study. These include well completion activities, gas compression plants, water treatment facilities, pipelines and downstream operations including LNG facilities. Emissions from some of these sources are often estimated for reporting purposes using methodology based on emission factors largely derived from the U.S. gas industry. However, reliable measurements on Australian facilities are yet to be made and the uncertainty surrounding these some of these estimates remains high.

References

Allen, D.T. Torres, V.M., Thomas, J., Sullivan, D.W., Harrison, M., Hendler, A., Herndon, S.C., Kolb, C.E., Fraser, M.P., A. Daniel Hill, A.D., Lamb, B.K., Miskimins, J., Sawyer, R.F., Seinfeld, J.H., 2013. Measurements of methane emissions at natural gas production sites in the United States. Proceedings of the National Academy of Science 110, 18023–18024.

Alverez, A.A., Pacala, S.W., Winebrake, J.J., Chameides, W.L., Hamburg, S.P., 2012. Greater focus needed on methane leakage from natural gas infrastructure. Proceedings of the National Academy of Science, 109, 6435-6440.

API, 2009. Compendium of greenhouse gas emissions methodologies for the oil and natural gas industry. American Petroleum Institute, Washington DC.

Brandt, A.R., Heath, G.A., Kort, E.A., O'Sullivan, F., Pétron, G., Jordaan, S.M., Tans, P., Wilcox, J., Gopstein, A.M., Arent, D., Wofsy, S., Brown, N.J., Bradley, R., Stucky, G.D., Eardley, D., Harris, R., 2014. Methane leaks from North American natural gas systems. Science 343, 733-735.

BREE, 2013. Energy in Australia 2013. Bureau of Resources and Energy Economics, Canberra (http://bree.slicedlabs.com.au/sites/default/files/files/publications/energy-in-aust/bree-energyinaustralia-2013.pdf, accessed 12 February 2014).

CAPP, 2002. Estimation of flaring and venting volumes from upstream oil and gas facilities. The Canadian Association of Petroleum Producers, Calgary. (http://www.capp.ca/library/publications/sourGasFlaringVenting/pages/pubInfo.aspx?DocId=38234, accessed 30 May 2014).

Crosson, E.R., 2008. A cavity ring-down analyzer for measuring atmospheric levels of methane, carbon dioxide, and water vapor. Applied Physics B 92, 403-408.

Day, S., Etheridge, D., Connell, N., Norgate, T. (2012). Fugitive greenhouse gas emissions from coal seam gas production in Australia. CSIRO Report EP128173. 28 pp.

Day, S., Dell'Amico, M., Fry, R., Javanmard, H. (2013). Preliminary field measurements of fugitive methane emissions from coal seam gas production in Australia. Proceedings of the 14th International Conference on Coal Science and Technology, Pennsylvania State University 29 Sept-3 Oct 2013, 1445-1455.

DEEDI, 2010. Leakage testing of coal seam gas wells in the Tara 'rural residential estates' vicinity. Department of Employment, Economic Development and Innovation, Brisbane. (http://www.dnrm.qld.gov.au/__data/assets/pdf_file/0011/119675/tara-leakage-csg-wells.pdf accessed 21 February 2014).

DIICCSRTE, 2013a. Australian national greenhouse accounts. National inventory report 2011, Volume 1. Department of Industry, Innovation, Science, Research and Tertiary Education, Canberra. (http://www.climatechange.gov.au/sites/climatechange/files/documents/05_2013/AUS_NIR_2011_Vol1.pdf, accessed 23 February, 2014).

DIICCSRTE, 2013b. Australian national greenhouse accounts. National greenhouse account factors. Department of Industry, Innovation, Science, Research and Tertiary Education, Canberra. (http://www.climatechange.gov.au/sites/climatechange/files/documents/07_2013/national-greenhouse-accounts-factors-july-2013.pdf, accessed 17 May 2014).

DNRM, 2014. Queensland's coal seam gas overview, January 2014. Queensland Department of Natural Resources and Mines, (http://mines.industry.qld.gov.au/assets/coal-pdf/csg-update-2014.pdf, accessed 11 February 2014).

Etiope, G., Drobniak, A., Schimmelmann, A., 2013. Natural seepage of shale gas and the origin of the 'eternal flames' in the Norther Appalacian Basin, USA. Marine and Petroleum Geology 43, 178-186.

Francey, R.J., Steele, L.P., Spencer, D.A., Langenfelds, R.L., Law, R.M., Krummel, P.B., Fraser, P.J., Etheridge, D.M.,Derek, N., Coram, S.A., Cooper, L.N., Allison, C.E., Porter, L., Baly, S., 2003.The CSIRO (Australia) measurement of greenhouse gases in the global atmosphere, report of the 11th WMO/IAEA. Meeting of Experts on Carbon Dioxide Concentration and Related Tracer Measurement Techniques, Tokyo, Japan, September 2001, S.Toru and S. Kazuto (editors), World Meteorological Organization Global Atmosphere Watch 97-111.

Hanna, S.R., Briggs, G.A., Hosker Jr., R.P., 1982. Handbook on atmospheric diffusion. U.S. Department of Energy, Technical Information Center (page 29).

Ingraffea, A.R., 2013. Fluid migration mechanisms due to faulty well design and/or construction: an overview and recent experiences in the Pennsylvania Marcellus play. Physicians, Scientists & Engineers for Healthy Energy. (http://psehealthyenergy.org/data/PSE__Cement_Failure_Causes_and_Rate_Analaysis_Jan_2013_Ingraffea1.pdf, accessed 24 February 2014).

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

Karion, A., Sweeney, C., Pétron, G., Frost, G., Hardesty, R.M., Kofler, J. Miller, B.R., Newberger, T., Wolter, S., Banta, R., Brewer, A., Dlugokencky, E., Lang, P., Montzka, S.A., Schnell, R., Tans, P., Trainer, M., Zamora, R., Conley, S., 2013. Methane emissions estimate from airborne measurements over a western United States natural gas field. Geophysical Research Letters 40, 4393–4397.

Kirchgessner, D.A., Lott, R.A., Cowgill, R.M., Harrison, M.R., Shires, T.M., 1997. Estimate of methane emissions from the U.S. natural gas industry. Chemosphere 35, 1365-1390.

Klusman, R.W., 1993. Soil gas and related methods for natural resource exploration. Wiley, Chichester, UK.

Miller, S.M., Wofsya, S.C., Michalak, A.M., Kort, E.A., Andrews, A.E., Biraude, S.C., Dlugokenckyd, E.J., Eluszkiewicz, J., Fischerg, M.L., Janssens-Maenhouth, G., Miller, B.R., Miller, J.B., Montzka, S.A., Nehrkorn, T., Sweeney, C., 2013. Anthropogenic emissions of methane in the United States. Proceedings of the National Academy of Science, 110, 20018–20022.

Pacific Environment Limited, 2014. AGL fugitive methane emissions monitoring program – technical report. (http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Camden/Assessments%20and%20Reports/2014/February/7081E_AGL_Fugitive_Methane_Monitoring_Program_Technical_Report_FINAL_Main%20Report.pdf, accessed 15 February 2014).

Pétron, G., Frost, G., Miller, B. R., Hirsch, A. I., Montzka, S. A., Karion, A., Trainer, M., Sweeney, C., Andrews, A. E., Miller, L., Kofler, J., Bar-Ilan, A., Dlugokencky, E.J., Patrick, L., Moore Jr., C.T., Ryerson, T.B., Siso, C., Kolodzey, W., Lang, P.M., Conway, T., Novelli, P., Masarie, K., Hall, B., Guenther, D., Kitzis, D., Miller, J., Welsh, D., Wolfe, D., Neff, W., Tans, P., 2012. Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. Journal of Geophysical Research-Atmospheres, 117. D04304.

Saddler, H., 2012. Review of literature on international best practice for estimating greenhouse gas emissions from coal seam gas production. Report prepared for the Department of Climate Change and Energy Efficiency. Pitt & Sherry. (http://www.climatechange.gov.au/sites/climatechange/files/media/March%202013/coal-seam-gas-methods-review-2012.pdf, accessed 26 February 2014).

Santos, I., Maher, D., 2012. Submission on estimation of fugitive methane from coal seam gas operations. (http://www.climatechange.gov.au/sites/climatechange/files/files/climatechange/nger/submission/CSG-20121109-CentreForCoastalBiogeochemistrySCU.pdf, accessed 15 February 2014).

Somerville, W., 2012. Submission on estimation of fugitive methane from coal seam gas operations. (http://www.climatechange.gov.au/sites/climatechange/files/files/climate-change/nger/submission/CSG-20121109-DrSomerville.pdf, accessed 31 January, 2014).

Tait, D.R., Santos, I. Maher, D.T., Cyronak, T.J., Davis, R.J., 2013. Enrichment of radon and carbon dioxide in the open atmosphere of an Australian coal seam gas field. Environmental Science and Technology 47, 3099–3104.

USEPA, 1995. Protocol for Equipment Leak Emission Rates. U.S. Environmental Protection Agency, Washington DC.

Wigley, T., 2011. Coal to gas: the influence of methane leakage. Climatic Change, 108, 601–608.

Appendix

Table A1. Results of the downwind traverse measurements for each well. The average results shown for Wells B2, B7 and C3 were measured on each well pad. All units are g min^{-1}.

Well Number	Average	Minimum	Maximum	Std Deviation
A1	0.04	0.03	0.11	0.03
A2 - Suspended	0.00	0.00	0.00	0.00
A3	0.04	0.02	0.08	0.02
A4	7.28	2.75	13.42	3.38
A5	0.10	0.08	0.20	0.06
A6	0.05	0.04	0.05	0.01
B1	1.50	0.01	3.60	1.22
B2	43.8 (on pad)	1.09	66.5	22.5
B3	0.07	0.01	0.28	0.08
B4	0.04	0.01	0.22	0.06
B5	0.01	0.01	0.02	0.00
B6	1.66	0.77	3.10	0.74
B7	1.27 (on pad)			
B8	1.31	0.10	2.85	0.98
B9	0.83	0.14	2.95	0.81
B10	0.15	0.07	0.28	0.07
B11	1.79	0.09	3.65	1.07
B12	0.05	0.01	0.12	0.03
B13	0.02	0.01	0.06	0.02
B14	0.61	0.01	3.23	0.98
B15	1.61	0.11	7.78	2.35
C1	8.69	2.73	15.9	4.77
C2	1.10	0.33	2.45	0.66

C3	28.0 (on pad)			
C4	11.8	0.46	34.8	12.4
C5	0.93	0.21	1.82	0.56
C6	1.17	0.07	2.38	0.71
C7	0.54	0.04	0.99	0.35
C8	0.10	0.02	0.27	0.08
C9	0.05	0.01	0.10	0.03
C10	1.75	0.76	3.52	0.82
C11	0.07	0.05	0.10	0.02
D1 Abandoned	0.00	0.00	0.00	0.00
D2	0.12	0.03	0.16	0.04
D3 Abandoned	0.00	0.00	0.00	0.00
D4	0.32	0.17	0.57	0.13
D5	1.07	0.11	2.18	0.71
D6	2.52	0.44	5.00	1.42
E1	2.17	0.63	4.08	1.19
E2	0.99	0.50	2.17	0.55
E3	0.60	0.22	1.13	0.33
E4	14.8	1.89	56.8	18.8
E5	0.06	0.01	0.19	0.06

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Summary of Public Comments and Responses: Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*

April 2017
U.S. Environmental Protection Agency,
Office of Atmospheric Programs, Washington, D.C.

Responses to Comments Received during the Public Review Period on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*

Preface

EPA thanks all commenters for their interest and feedback on the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Per Federal Register Notice FRL–9959–29–OAR published on February 15, 2017 the Environmental Protection Agency (EPA) announced document availability and request for comments on the draft “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015” report. The EPA requested recommendations for improving the overall quality of the inventory report to be finalized in April 2017 and submitted to the United Nations Framework Convention on Climate Change (UNFCCC), as well as subsequent inventory reports.

During the 30-day public comment period, EPA received 47 unique comments in response to the notice. This document provides EPA’s responses to technical comments on methods and data used in developing the annual greenhouse gas inventory. The verbatim text of each comment extracted from the original comment letters is included in this document, arranged by commenter. EPA’s responses to comments are provided immediately following each comment excerpt.

Commenter: 3M Electronics Materials Solutions Division

Kurt Werner

Comment: *Suggested Revisions to Table A-146: Fire Extinguishing Market Transition Assumptions*. 3M's assumptions with regard to market share transition from halons to HFCs and Non ODP/GWP alternatives are very different than what is reflected in Table A-146, especially the assumption that the market for HFC-227ea in the mid to late 1990s is only 18% of the original halon market. 3M fully recognizes that, due to cessation of discharge testing and pricing of substitute agents, the clean agent market was substantially smaller after the phase-out of halon. The assumptions in A-146, however, do not appear to consider the technology boom of the late 1990s or the fact that substantially more HFC is necessary per protected space than halon. Appendix I includes the original Table A-146 and a second Table A-146 with 3M recommended edits.

As you consider updating the U.S. inventory of GHG emissions, please consider these comments related to the fire suppression sector. The market dynamics impacting the evolution and uptake of halon alternatives has meaningfully changed since the original assumptions were established. Please also note that some of the original assumptions with regard to the size of halon replacement may need to be considered. Contrary to voluntary industry reporting, measured atmospheric concentration suggest that emissions of HFCs from the fire suppression continue to rise and this should not be surprising given the increasing installed base of HFC fire suppression systems. Future HFC emission rate estimates from the fire suppression sector should also consider that the secondary market for HFCs in fire suppression is saturated and there is essentially no market for recovered HFC-227ea.

Response: **As new fire suppressants enter the market, the U.S. EPA's Vintaging Model does account for the relative quantity of fire suppressant used in fire protection systems by using replacement ratios, with 1 kilogram of halon as the basis. These replacement ratios are chemical-specific, constant, and are based on NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems and industry estimates. EPA will consider adopting the suggested market penetration revisions (shared separately by 3M) to Table A-146.**

EPA looks forward to working with the commenter during the peer review of the Vintaging Model to understand the following: data sources informing the proposed market transition assumptions; information supporting the suggestion that all HFC-227ea will be emitted (rather than incinerated or recycled) as systems are decommissioned in a saturated secondary market where there is no market for recovered HFC-227ea; and how the global atmospheric concentration of HFC-227ea estimated by Laube et al. (2010) can quantitatively inform historical and projected emissions from the total flooding protection sector in the United States.

Commenter: American Fisheries Society

Robert M. Hughes

Comment: I agree with the importance of forests and grasslands as C sinks. And I agree that wood harvested for energy production should be treated as a C emission. I agree with using the FIA estimates of wood volume to arrive at national estimates of forest C, as well as the NRCS estimates of soil C for estimating grassland C. I also agree with the need to obtain accurate estimates of soil C status and trends for Alaska grasslands & wetlands. I believe there are large stores of C in those systems, and as they dry and warm they will release C.

***Response:* EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Comment: I am unclear and concerned about the accuracy of the CH4 estimates from the oil and gas industry. Unlike the USDA, industry reports suffer from both real and potential conflicts of interest. I am particularly concerned with unreported CH4 leakage from fracked wells, rock, and water sources. In addition, I am concerned about inaccurate well counts, inaccurate well locations, and incomplete/faulty sealing of abandoned and inactive wells.

***Response:* The Inventory uses a variety of data sources to calculate emissions of CH_4 from oil and gas, and conducts QA/QC and Verification activities on the data. Please see the QA/QC and Verification section in 3.5 Petroleum Systems and 3.6 Natural Gas Systems. Methane emissions from hydraulically fractured completions and workovers are included in the production segment emission for both petroleum and natural gas systems. The Inventory has been revised to use updated well count data; see the Recalculations Discussion section in 3.5 Petroleum Systems and 3.6 Natural Gas Systems. Emissions from abandoned wells are discussed in the Planned Improvements section of both 3.5 Petroleum Systems and 3.6 Natural Gas Systems. Well location information is not used in the calculation of the Inventory.**

Commenter: American Petroleum Institute

Karen Ritter

Comment: *Specific Correction for Petroleum Systems Data***.** *In Tables 3-36 and 3-37, the numbers presented do not sum to the total for Production Field Operations. In the previous national inventory, EPA included a line item for miscellaneous venting and flaring to include the sum of all other sources not listed. This line should be added to both tables for the final report.*

***Response:* The table has been updated in the final Inventory. Please see 3.5 Petroleum Systems.**

Comment: *Transparency***.** The Annex Tables 3.5 and 3.6 provide the emission factors, activity data, and resulting CH4 emissions for every source across the full time series (1990-2015). This level of detail has not been provided previously. API supports these tables as an addition to the information previously provided in the inventory annex sections for petroleum systems and natural gas systems. Specifically, API requests that EPA maintain the detail provided in the annexes from previous GHGI reports in addition to the new tables.

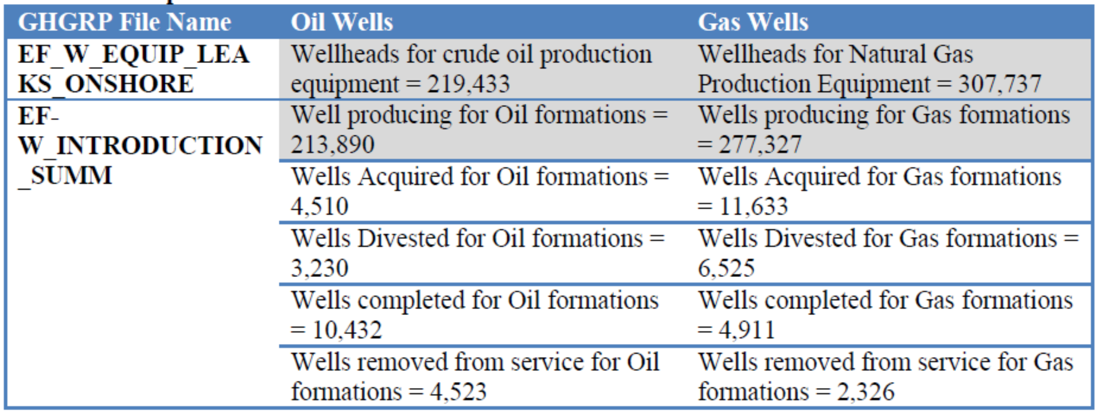
API also requests that numeric tables be provided to stakeholders in Excel format. Annex Tables 3.5 and 3.6 also provide considerable abbreviated descriptions of the data sources for the emission factors and activity data. More detail is needed for some sources to fully understand how EPA developed the final data that is used for the emissions calculations. For example, the Petroleum Systems annex notes that counts of storage tanks in the Production segment for 2011-2015 are based on 2015 GHGRP Subpart W data. However, there is neither discussion of how these counts were extrapolated from the Subpart W reports to a national level nor any discussion of how the 2015 data were used to apply to the years

2011-2014. API requests additional transparency for emission sources where multiple steps are used to derive either the activity data or the emission factor.

Response: **For the final Inventory, EPA has provided the annex tables reported in previous Inventory reports, the additional level of detail provided in the Public Review draft, and an expanded data discussion, in Excel format. Please see https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg.**

Comment: *Well Counts***.** API has addressed EPA's update to well counts in its letter of 1/27/2017 as part of the expert review of EPA's proposed methodology updates for Natural Gas and Petroleum Systems Production emissions. API continues to support the proposed revised methodology and has indicated that the well counts described in the agency's memo result in EPA's revised well count aligning with, and becoming far more comparable to, other data sources (such as Energy Information Administration, World Oil, Independent Petroleum Association of America, and API's queries of DI Desktop). API welcomes EPA's indication that it received feedback where other stakeholders generally support the revised well counts and agree that it introduces more consistency with recently published well count estimates. API is looking forward to the results of EPA's further comparison of current estimates with stakeholders' well counts also derived from DrillingInfo, investigation of differences, and establishing revised well counts in the final Inventory. API understands that this may potentially result in additional changes to calculated emissions from sources that rely on oil well counts for activity data (e.g., pneumatic controllers, equipment leaks, and storage tanks). A large number of the national equipment counts used in both petroleum systems and natural gas systems production are based on scaling well counts from the GHGRP. Based on API's review of the public review draft of the GHGI, it appears that EPA derives the GHGRP 2015 well counts from the major equipment count reported for Equipment Leaks (file EF_W_EQUIP_LEAKS_ONSHORE). However, API notes that these counts differ from the well data reported under 98.236(aa) (File EF_W_INTRODUCTION_SUMM), as shown in Table 1 below. EPA needs to resolve the differences between these two numbers reported through the GHGRP. API contends that the well counts reported under the sector summary information are more reliable.

Table 1. Comparison of Well Counts



GHGRP File Name	Oil Wells	Gas Wells
EF_W_EQUIP_LEAKS_ONSHORE	Wellheads for crude oil production equipment = 219,433	Wellheads for Natural Gas Production Equipment = 307,737
EF-W_INTRODUCTION_SUMM	Well producing for Oil formations = 213,890	Wells producing for Gas formations = 277,327
	Wells Acquired for Oil formations = 4,510	Wells Acquired for Gas formations = 11,633
	Wells Divested for Oil formations = 3,230	Wells Divested for Gas formations = 6,525
	Wells completed for Oil formations = 10,432	Wells completed for Gas formations = 4,911
	Wells removed from service for Oil formations = 4,523	Wells removed from service for Gas formations = 2,326

Response: **In the current Inventory, EPA has included updated well counts natural gas and petroleum systems. See the Recalculations Discussion sections in 3.5 Petroleum Systems and 3.6 Natural Gas Systems. EPA will update the next Inventory with resubmitted data, which may result in minor changes in equipment counts per well for 2015.**

Comment: *Data Quality***.** API reiterates that the EPA should carefully analyze and screen Subpart W reported data in order to improve the validity of data used in the national GHGI. EPA should have an established procedure for identifying obvious data errors and/or outliers, and for correcting or excluding those outliers to prevent disproportionately impacting the derivation of emission factors (EFs) or extrapolation of potentially erroneous information for inclusion in the national GHGI.

In addition, as EPA is evaluating data available from new studies, it is important to understand the applicability of these studies for a national inventory. API reiterates the need to vet new studies and data through a multi-stakeholder group prior to updating the GHGI. API proposes that such a working group be convened following the completion of the 2017 GHGI to provide a structured framework, and agreed upon timeline, for consultation and review of GHGI updates. An early start (April 2017) and frequent meetings (every 1-2 months) would provide sufficient time to review and consolidate "developing" information in an informed process for updating the 2018 GHGI and beyond.

Response: **EPA has a multi-step data verification process for GHGRP data, including automatic checks during data entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[1] See the QA/QC and Verification discussion in 3.5 Petroleum Systems and 3.6 Natural Gas Systems. Information on EPA's stakeholder process for the 2018 Inventory is available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.**

Comment: *Associated Gas Venting and Flaring***.** Significant changes have been made to estimating emissions from associated gas venting and flaring in the RY 2015 inventory compared to previous years which addressed only stripper wells. This is an area that requires further study because operational practices that result in either venting or flaring are linked to the availability of appropriate infrastructure to capture and use associated gas, rather than vent or flare it. This is a dynamic situation that varies from year to year and from region to region, and requires further analysis of information available through the GHGRP.

Response: **For the current Inventory, the associated gas venting and flaring estimates have been updated to use year-specific 2011 through 2015 GHGRP data for the years 2011 through 2015 in the Inventory, and an estimate based on 2011 GHGRP data and assumptions about flaring earlier in the times series for 1990 through 2010. EPA agrees that these practices can vary and continues to seek information on associated gas venting and flaring, in particular for earlier years of the time series; please see the Planned Improvements discussion in 3.5 Petroleum Systems.**

Comment: *Gas Processing Compressors***.** API's analysis for gas processing compressor's average emission factors was previously presented to EPA in a letter of 2/13/2017 (including attachments and technical memoranda). API recommends that emission factors be derived based on average GHGRP data from 2013 through 2015 to account for the variability in measured components and the use of controls. Furthermore, API recommends that going forward it may be appropriate to use the GHGRP data reported for compressor emissions each year, or on a rolling three-year average, depending on data variability in future years.

***Response*:** **For the current Inventory, the gas processing compressors estimates were updated to use data from EPA's GHGRP, for the year 2015. EPA will consider refinements to these estimates, such as**

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[1] https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf

use of additional years of GHGRP data and/or using a rolling 3-year average of GHGRP data, for future Inventory reports. Please see the Planned Improvements section of 3.6 Natural Gas Systems.

Comment: *Abandoned Wells***.** EPA indicates that it is seeking emission factors and national activity data available to calculate emissions from abandoned wells. API contends that this is an area that requires further study and determining a national count of abandoned wells will be challenging. API cautions EPA that current studies (Townsend-Small et al. 2016 and Kang et al. 2016) are limited in scope and should not be extrapolated broadly.

Response**: EPA agrees that associated gas wells require further study. Please see the Planned Improvements section of 3.6 Natural Gas Systems and 3.5 Petroleum Systems.**

Comment: *Gas STAR Reductions***.** API agrees that many emissions sources in the GHGI are now calculated using net emissions approaches, with technology-specific activity data and emission factors, and annual data from the GHGRP. For these emission sources it may not be necessary to adjust for Natural Gas Star reductions, which may result in double-counting of reductions. Removing the Natural Gas Star reductions from these sources would improve transparency of the results and methods by relying on direct net emission calculations. However, where applicable, EPA should continue to apply the Natural Gas Star reductions for those specific sources for which only potential emission data is available.

Response: **We agree that Gas STAR reductions should be removed for sources which are calculated with net emissions approaches. In the Inventory, Gas STAR reductions have been removed from the petroleum production segment and the natural gas processing segments, which are now calculated using a net emissions approach. For the natural gas production segment, though many sources in production are now calculated with net factor approaches, several sources are calculated with potential emissions approaches, and therefore some of the Gas STAR reductions are subtracted from the production segment estimates. To address potential double-counting of reductions, a scaling factor is applied to the "other reductions" to reduce this reported amount based an estimate of the fraction of those reductions that occur in the sources that are now calculated using net emissions approaches. The fractions were recalculated in the current Inventory to take into account that tanks are now calculated with net emissions approaches, and to address minor errors in the previous calculation. Please see the Recalculations Discussion section of 3.5 Petroleum Systems and 3.6 Natural Gas Systems.**

Commenter: Applied Geosolutions and World Resources Institute

Stephen Hagen and Nancy Harris

Comment: *Area of forest land converted to grassland***.** Table 6-7 indicates that nearly 4.6 million hectares of forest land were converted to non-forest land each year over the last five years, 4 million hectares of which were converted to grassland. This number seems high, given that forest land to grassland conversion in the lower 48 states between 2006 and 2011 was approximate 1 million ha/yr on average, as estimated from NLCD data. While we recognize the mismatch in years of analysis (2006-2011) and that NRI rather than NLCD is the source of data used for estimating this conversion type in the lower 48 states, the rate of conversion of forest land to grassland estimated using NRI data is about four times higher than estimates derived from NLCD. The acknowledgement of this difference, as well as the inclusion of some language of clarification in the inventory, seems warranted.

Given the combination of data sources used in the inventory to represent the U.S. land base, it is also unclear in the inventory draft how much, if any, of this forest land to grassland conversion occurred in managed lands in Alaska, where NLCD is the data source used to determine transitions yet no NLCD data are currently available for years past 2011. The 2001 to 2011 NLCD product estimates that approximately 0.3 million ha/yr of forest land is converted to grassland in Alaska. Notwithstanding this fact, it is our experience that changes in land cover, as provided by the NLCD, are not always changes in land use. Specifically, a loss of tree cover associated with a clear cut harvest can appear in NLCD as a change from forest land to grassland, but if the land is intended to regrow into forest, the land use is to remain forest land. It is also our understanding that emissions associated with harvest are accounted for in the Forest Land Remaining Forest Land and Harvested Wood Pools section (pages 6-23, 6-24). While we have no evidence of double counting here, we want to note this possibility and request clarification.

***Response*: The amount of area classified as Forest Land Converted to non-Forest Land is the cumulative total over a 20-year period, and not the annual conversion. The *IPCC Guidelines* require that land converted to another land use remain in the land use conversion category for 20 years (e.g., *Forest Land Converted to Grassland*), and this is the reason for the 20-year cumulative total, instead of just the amount of land converted on an annual basis. In addition, the source of the Forest Land use conversion data is the Forest Inventory and Analysis (FIA) program data, and not the National Resources Inventory (NRI).**

There are tables with more detailed information about the land representation, including state totals, but these are not typically included in the Inventory report. EPA will consider including this more detailed information in the next Inventory report. There may be some areas in Alaska where the land has been subject to a clear cut operation, leading to a land cover classification as grassland, but the land is still managed as a forest. EPA will conduct additional analysis in the future in an attempt to capture some of these areas, but there will always be some limitations without a survey of the land owners/managers to understand the specific use of the land. EPA will also further investigate the possibility of double-counting the losses for forest land conversion in Alaska.

Comment: *Carbon stock change factor for forest land converted to grassland***.** An additional key factor in reporting carbon stock changes resulting from the Conversion of Forest Land to Grassland is the stock change factor and associated reporting assumptions applied. Forest lands typically have significantly higher above- and below- ground biomass densities than grasslands and thus conversion from forest land to grassland can result in high carbon losses. It is our understanding that the draft inventory makes use of measurements from FIA plots to estimate the forest land above ground forest carbon density and an IPCC Tier 1 default value for the post-change above ground grassland carbon density. This IPCC default, represented as an average value (+/- uncertainty) across a broad ecoregion type, may not be representative of the average measured carbon density in US grassland ecosystems. If IPCC defaults are substantially lower than measured C densities in US grasslands the result would be an overestimate of carbon loss from this transition. IPCC Guidelines encourage the use of Tier 2 country-specific factors where available. We encourage the inventory team to explore the use of a carbon density value of grasslands that accurately represents US grasslands to replace the IPCC default in the case of transition of forest land to grassland.

***Response:* The Inventory Team identified that the IPCC Tier 1 approach and default stock estimates used in the Public Review version of the Inventory may not accurately characterize the carbon stock transfers from Forest Land to Grasslands in the Great Plains and Western United States. The team**

undertook additional analyses during the Public Review period that included a more refined disaggregation of land use changes using Forest Inventory and Analysis data. These analyses included estimation of state-specific carbon stock estimates for grasslands where a fraction of the carbon stocks from forest land are transferred to the grassland land use category rather than assuming all carbon is lost to the atmosphere in the year of conversion. Please see the Land Converted to Grasslands section for details on the refined disaggregation of land use changes and the estimation of state-specific grassland carbon stocks, which resulted in changes in the estimates reported in the Public Review version of the Inventory. To learn more, review the Supplementary USFS Briefing Paper and Technical Summary available here: ***https://www.epa.gov/sites/production/files/2017-04/documents/usfs_brief_techsummary.pdf***

Commenter: Center for Carbon Removal

Jason Funk

Comment: We noted significant changes to the estimates of the magnitude of the historical U.S. LULUCF sink in the Draft Inventory, compared to estimates from previous years. In some cases, these revisions changed previous estimates in a way that decreased the magnitude of the overall sink by more than 50 percent, compared to estimates for the same year in previous Inventories. Upon further investigation, we found that these significantly revised estimates appear to arise from a reclassification of lands that formerly met the national definition of forest land, but have now been reclassified as grasslands because they no longer meet one or more of the criteria of the forest land definition. Furthermore, the estimates of biomass in these newly reclassified grasslands appear to rely on Intergovernmental Panel on Climate Change (IPCC) default values, consistent with a Tier 1 approach. We commend the efforts in this draft to improve the quality and transparency of the information used to develop the Inventory. In this case, we are concerned that the use of IPCC default values for U.S. grassland carbon stocks may actually diminish the accuracy of the estimated emissions from these lands, and hence of the entire inventory. Since this single factor seems to account for a change in the emissions estimate on a scale of hundreds of millions of tons CO2-e, it seems important to construct the most accurate estimate possible.

In our view, while the 2006 IPCC Guidelines allow for the use of Tier 1 data when necessary, it is good practice for countries to use country-level (Tier 2) or spatially explicit data (Tier 3) whenever possible. And in this case, the Tier 1 default values are probably not representative of the carbon stocks in lands that were recently forested. In many cases, these areas may still have significant amounts of carbon present in woody material in above- or below-ground biomass, dead wood, and litter, as well as in soil organic matter. To represent these areas with default values for grasslands likely significantly overestimates the emissions from these lands, in a way that diminishes the accuracy of the Inventory, rather than enhancing it. We have come to understand that Tier 2 and Tier 3 data related to carbon stocks in areas newly classified as "forest land converted to grassland" may be available from federal agencies (including the US Forest Service, Bureau of Land Management, and possibly others), national laboratories, academic institutions, and other sources. We request that EPA undertake a robust effort to identify and utilize such information in subsequent development of the Draft Inventory. In our view, the use of Tier 1 emission factors for these areas is not consistent with good practice, and we urge EPA to develop an Inventory that fulfills the IPCC principles to the greatest possible degree.

Response: **The Inventory Team identified that the IPCC Tier 1 approach and default stock estimates used in the Public Review version of the Inventory may not accurately characterize the carbon stock**

transfers from Forest Land to Grasslands in the Great Plains and Western United States. The team undertook additional analyses during the Public Review period that included a more refined disaggregation of land use changes using Forest Inventory and Analysis data. These analyses included estimation of state-specific carbon stock estimates for grasslands where a fraction of the carbon stocks from forest land are transferred to the grassland land use category rather than assuming all carbon is lost to the atmosphere in the year of conversion. Please see the Land Converted to Grasslands section for details on the refined disaggregation of land use changes and the estimation of state-specific grassland carbon stocks which resulted in changes in the estimates reported in the Public Review version of the Inventory. To learn more, review the Supplementary USFS Briefing Paper and Technical Summary available here:
https://www.epa.gov/sites/production/files/2017-04/documents/usfs_brief_techsummary.pdf

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Commenter: Climate Accountability Institute

Richard Heede

Comment: I fully support the annual publication of the US GHG inventory. I rely on it in my own work, it is an essential foundation for the data submitted to the UNFCCC, and it is critical that this work be funded and continued. Please tell Administrator Pruitt to support its publication and continuance. Data is not political.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Climate Action Reserve

Trevor Anderson

Comment: Thank you EPA for your continued commitment to submit and publish annual GHG inventory reports and for helping the USA meet its UNFCCC treaty obligations. The USA has been a leading developer of new and improved methodologies for estimating emissions and sinks, and I'd like to see it continue to be one. I use and rely on GHG estimation methods and U.S. GHG data daily at my job and so do countless others across the globe. They are of critical importance, and as a U.S. citizen, I am personally proud the U.S. inventory continues to be such a high quality analysis.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Climate and Land Use Alliance

Donna Lee

Comment: I wanted to thank you for the transparency you provide on US emissions and removals and the opportunity for public comment. The US is an important country when it comes to climate change and the data and information you generate is critical to ensuring we avoid what could be very expensive needs in the future from global warming impacts. In general, having looked at many GHGIs across the world, the US inventory is well written and organized (many countries could usefully emulate the US documentation); the level of detail provided is also extremely useful.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Comment: The most noticeable difference in the 2017 draft is the reduction in the land sector sink. While there is a short explanation of methodological changes that have occurred that may explain the significant difference in quantification (especially F>GL and F>Settlements), it may be useful to provide a bit clearer explanation and some sense of where method changes resulted in the largest quantified changes (e.g. was it the addition of new transitions, new pools for those transitions, or changes in the model itself?)

Response**: In finalizing the 1990 through 2015 Inventory, EPA made several methodological changes from the Public Review version that resulted in reduced losses of carbon from conversion of forest lands to croplands, grassland and settlements. These changes are fully documented in the final 1990 through 2015 Inventory under the "Methodology" and "QA/QC and Verification" sections of 6.5 Land Converted to Cropland, 6.7 Land Converted to Grassland, and 6.11 Land Converted to Settlements. To learn more, review the Supplementary USFS Briefing Paper and Technical Summary available here:** ***https://www.epa.gov/sites/production/files/2017-04/documents/usfs_brief_techsummary.pdf***

Comment: It seems one key (new) "source" category is F>GL, but there is no explanation of what is driving this change. It may be that (spatially explicit) data is not available, but it seems to be critical for policymaking. I've continued to look at the GHGI numbers, particularly the significant reduction in the total (net) land sector sink... and was concerned about the large new source related to forest conversions (in particular, forests converted to grasslands). I applaud your efforts to include these new conversions in the inventory, per IPCC guidelines... although, I wonder if it may be worth reexamining the methods you used for this new transition category? It seems rather critical, given its impact on the overall land sector sink.

Response: **Please see the response to the question above.**

Comment: The GHGI states that Agroforestry systems that meet the definition of forest land are not included in the GHGI as they are not currently inventoried by the US. I assume this is simply a current gap. It would be useful to understand how significant are such systems (i.e. how big is the gap)?

Response: **The United States does not have reliable databases at this time that can be used to estimate carbon stocks or stock changes on Agroforestry systems. Research efforts are underway by USDA to develop an approach that will use data from the National Resources Inventory, but it will be several years before the data is available for use in the Inventory. While the carbon stocks of these Agroforestry lands may be substantial, preliminary indications are that on a national level the carbon stocks are not likely to be changing significantly through growth or loss.**

Comment: Page 6-31, line 50-51: "reduces the managed forest area by approximately 5%" - is this 5% of total managed forest area, or just the managed forest areas in Alaska?

Response: **The 5 percent reduction is referring only to the managed forest area in southeastern/southcoastal Alaska. Please see page 6-32 of the final 1990 through 2015 Inventory under the Recalculations Discussion section of *Forest Land Remaining Forest Land*; this has been clarified in the text.**

Comment: Table 6-84: Small issue, but it was really nice in this Table to have total figures for F > Settlement (in bold, followed by the breakdown by pool); in other transitions (F > Cropland, F > Grassland) there was no total, so I had to add up the various pools myself to get the totals.

Response**: In the final 1990 through 2015 Inventory, Tables 6-31, 6-32, 6-41 and 6-42 have been updated to provide totals for each conversion category.**

Commenter: Climate Trust

Jacoba Aldersebaes

Comment: Thank you for the EPA's ongoing commitment to update the United States' sources and sinks of Greenhouse Gas emissions. I'm writing to strongly urge the EPA to continue this work for many years to come. The Inventory has been an essential source over the years for determining innovative activities on behalf of businesses and landowners. As one such example, the foundation provided by the Inventory has directly contributed to our efforts to design a first of its kind market transaction to financially reward farmers for conserving grasslands. Looking forward the opportunities to engage land-based emission reduction projects is poised to grow and the continued publication of updated information will no doubt guide future initiatives.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Climate Trust

Matthew Baird

Comment: Thanks for your continued work to maintain a national greenhouse gas inventory report. Not only does it meet the UNFCCC treaty, but it provides a foundation of climate change policy. It would be impossible to significantly reduce greenhouse gases without something to measure against.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Comment: As the country looks at natural gas as a transition fuel from coal, I encourage the EPA to look at methane leakage at gas extraction sites. The full life-cycle of a fossil fuel should be understood as all GHG emissions affect the world, not just where they're burned. Some studies show that natural gas may be worse than coal when considering the methane that is leaked during extraction.

Response: **The Inventory reports emissions from natural gas production in section 3.5 Natural Gas Systems. In 2015, methane emissions from the natural gas production segment were 107 MMT CO_2 Eq.**

Commenter: Climate Trust

Mik McKee

Comment: Thank you for the EPA's ongoing commitment to update the United States' sources and sinks of Greenhouse Gas emissions. I'm writing to strongly urge the EPA to continue this work for many years to come. The Inventory has been an essential source over the years for determining innovative activities on behalf of businesses and landowners. As one such example, the foundation provided by the Inventory has directly contributed to our efforts to design a first of its kind market transaction to financially reward farmers for conserving grasslands. Looking forward the opportunities to engage land-based emission reduction projects is poised to grow and the continued publication of updated information will no doubt guide future initiatives.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Climate Trust

Peter Weisberg

Comment: Thank you for the EPA's ongoing commitment to update the United States' sources and sinks of Greenhouse Gas emissions. I'm writing to strongly urge the EPA to continue this work for many years to come. The Inventory has been an essential source over the years for determining innovative activities on behalf of businesses and landowners. As one such example, the foundation provided by the Inventory has directly contributed to our efforts to design a first of its kind market transaction to financially reward farmers for conserving grasslands. Looking forward the opportunities to engage land-based emission reduction projects is poised to grow and the continued publication of updated information will no doubt guide future initiatives.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Climate Trust

Sheldon Zakreski

Comment: Thank you for the EPA's ongoing commitment to update the United States' sources and sinks of Greenhouse Gas emissions. I'm writing to strongly urge the EPA to continue this work for many years to come. The Inventory has been an essential source over the years for determining innovative activities on behalf of businesses and landowners. As one such example, the foundation provided by the Inventory has directly contributed to our efforts to design a first of its kind market transaction to financially reward farmers for conserving grasslands. Looking forward the opportunities to engage land-based emission reduction projects is poised to grow and the continued publication of updated information will no doubt guide future initiatives.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Dogwood Alliance

Tyson Miller

Comment: At Dogwood Alliance, we appreciate all that the EPA does and support EPA's evolving work on carbon accounting in the new US greenhouse gas emission inventory. We specifically want to commend what we interpret as more accurate accounting compared to previous years. As an example, in Section 6.1 (pg 369/370), the tables show a decrease in forest carbon stocks from 1990 - 2015 and we feel that this new accounting approach shows a more accurate methodology and appreciate model updates that reflect this dynamic on the ground.

Response: **In finalizing the 1990 through 2015 Inventory, EPA made several methodological changes from the Public Review version that resulted in reduced losses of carbon from conversion of forest lands to croplands, grassland and settlements. These changes are fully documented in the final 1990 through 2015 Inventory under the "Methodology" and "QA/QC and Verification" sections of 6.5 Land Converted to Cropland, 6.7 Land Converted to Grassland, and 6.11 Land Converted to Settlements. To learn more, review the Supplementary USFS Briefing Paper and Technical Summary available here: https://www.epa.gov/sites/production/files/2017-04/documents/usfs_brief_techsummary.pdf**

Comment: In terms of suggestions for improving the methodology, Dogwood Alliance believes that while it is good that EPA is now counting emissions from forest fires separately, the agency should also separate out emissions from logging, as logging represents a larger share of carbon loss/emissions in forests. (See new carbon accounting framework approach published in Carbon Balance and Management for reference). We also feel that full accounting for emissions from soil disturbance due to logging using the latest methodologies is critical and are unsure whether the new methodology is integrating heterotrophic emissions.

Response**: While the carbon losses from timber harvesting are not explicitly reported in the Inventory, they are inherent in the carbon stocks and stock changes reported within the *Land Converted to Forest Land* and *Forest Land Remaining Forest Land* sections. Further, the products in use and land filled are included with Harvested Wood Products reported in the *Forest Land Remaining Forest Land* section. The Inventory Team continues to refine approaches allowing for more spatially and temporally resolved estimates of carbon stocks and stock changes associated with the Forest Land category including changes associated with natural and anthropogenic disturbances. Members of the Inventory Team were collaborators on the Harris et al. 2016 paper in CBM and this represents some of the research currently underway to improvement estimation and reporting in the Forest Land category.**

The new modeling framework for estimating soil carbon stocks and stock changes is based on Forest Inventory and Analysis data and broad climate and geological data. This approach was developed to use plot-specific information that is available nationally. At this time respiration is not explicitly

included in the modeling framework. As additional soil attributes become available the modeling framework with be re-evaluated and improvements will be made.

Commenter: Environmental Defense Fund and Colorado State University

David Lyon

Comments: *Technical Recommendations for Revision to Revisions to Draft 2017 GHGI.* EDF supports EPA's efforts to continuously improve the Inventory by incorporating the best available data, but we are concerned that the lower estimate of total methane emissions from Petroleum and Natural Gas Systems in the Draft 2017 GHGI, compared to the 2016 GHGI, does not agree with recent data. Although some of the agency's revised methodologies are rigorous and well-supported, the Draft 2017 GHGI fails to fully account for superemitters. If properly accounted for, emissions from these sources would likely counteract the agency's proposed downward revisions and, result instead in total Petroleum and Natural Gas System methane emissions that are similar to or slightly higher than the 2016 GHGI estimate of 9.8 Tg CH4.

Response: **EPA will continue to assess studies that include and compare both top-down and bottom-up estimates and could lead to improved understanding (e.g., identification of emission sources and information on frequency of high emitters) of unassigned high emitters or "super emitters," as recommended in stakeholder comments. See the Planned Improvements sections in 3.5 Petroleum Systems and 3.6 Natural Gas Systems.**

Comments: *Major Methodological Changes.* In the 2016 GHGI, EPA estimated 2014 methane emissions from Petroleum and Natural Gas Systems (O&G) are 9.8 Tg CH4.8 In the Draft 2017 GHGI, EPA revised 2014 emission estimates to 8.3 Tg CH4 based on several methodological changes to sources in the production and processing segments. The largest changes in emission estimates are due to two methodological revisions: 1) an updated method to estimate oil well count activity data, and 2) the use of EPA Greenhouse Gas Reporting Program (GHGRP) data to estimate processing plant emissions. As discussed in our stakeholder feedback on EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Revisions Under Consideration for Natural Gas and Petroleum Systems Production Emissions* (Production Memo), we agree that the revised oil well counts are more accurate than previous estimates.

Regarding the second change, we are concerned that the current method of utilizing GHGRP data underestimates processing sector emissions. The Draft 2017 GHGI estimate of 445 Gg CH4 is approximately 20% lower than the estimate of 546 Gg CH4 in a 2016 study by Marchese et al.10 We believe the Marchese et al. estimate is a more accurate estimate of national processing sector emissions because it is based on a study with industry participation that collected emissions data at 16 processing plants across the U.S. As discussed in our joint stakeholder feedback with Colorado State University on *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Updates Under Consideration for Natural Gas Systems Processing Segment Emissions* (Processing Memo),11 we recommend a method that uses the Marchese et al. estimate of processing plant emissions to scale up GHGRP-based source-specific emission estimates so that total emissions agree with the national study while providing the detailed source breakdown of the GHGRP method currently used in the Draft 2017 GHGI.

Response: **In the 1990 through 2015 Inventory, EPA updated the emission estimates for processing plants using data from the over 400 plants which have been reporting annual data to EPA's GHGRP since 2011. Data reported to EPA's GHGRP undergo a multi-step verification process, as discussed in the QA/QC and Verification section of 3.6 Natural Gas Systems. As noted in the Planned Improvements section of 3.6 Natural Gas Systems, EPA will continue to review data from new studies which may be used to update the Inventory.**

Comment: *In general, EDF supports the revised methodologies for production sector liquids unloading, storage tanks, and associated gas venting, but we have some concerns about the underlying data. As discussed in our feedback to the Production Memo, we recommend that EPA carefully quality assure the GHGRP data used in the GHGI emission estimates. Our response to the memo also addressed concerns about potential issues related to GHGRP reporting methodologies such as the use of emission factors for small tanks. In particular, EPA should evaluate the accuracy of tank control efficiencies reported to the GHGRP. As supported by the EPA compliance alert,12 Noble Consent Decree,13 and a national helicopter-based infrared camera survey of over 8,000 well pads in 7 U.S. basins,14 many controlled storage tanks may have higher emissions than expected due to poor design or malfunctions of their tank control systems. If tank control issues are not reported to the GHGRP, then the Draft 2017 GHGI method will underestimate storage tank emissions.*

Response: **Data reported to EPA's GHGRP undergo a multi-step verification process, as discussed in the QA/QC and Verification section of 3.6 Natural Gas Systems and 3.5 Petroleum Systems. As noted in the Planned Improvements section of 3.5 Petroleum Systems and 3.6 Natural Gas Systems, EPA continues to seek new data that could be used to update or assess the estimates in the Inventory, including tank malfunction and control efficiency data.**

Comment: *EPA Should Avoid Double-Counting Emission Reductions.* As noted in the Draft 2017 GHGI, the calculation of net emissions obviates the application of regulatory or voluntary emission reductions, which were previously applied to potential emission estimates to account for changes in equipment and practices following the development of potential emission factors. Since the Draft 2017 continues to apply Natural Gas STAR based voluntary reductions to sources that now are calculated as net emissions, some reductions will be double counted, and therefore, the GHGI will underestimate emissions. In the final 2017 GHGI, EPA should no longer apply regulatory or voluntary emission reductions to sources that are based on net emission calculations.

Response: **EPA agrees that Gas STAR reductions should be removed for sources which are calculated with net emissions approaches. In the Inventory, Gas STAR reductions have been removed from the petroleum production segment and the natural gas processing segments, which are now calculated using a net emissions approach. For the natural gas production segment, though many sources in production are now calculated with net factor approaches, several sources are calculated with potential emissions approaches, and therefore some of the Gas STAR reductions are subtracted from the production segment estimates. To address potential double-counting of reductions, a scaling factor is applied to the "other reductions" to reduce this reported amount based an estimate of the fraction of those reductions that occur in the sources that are now calculated using net emissions approaches. The fractions were recalculated in the current Inventory to take into account that tanks are now calculated with net emissions approaches, and to address minor errors in the previous calculation. Please see the Recalculations Discussion section of 3.5 Petroleum Systems and 3.6 Natural Gas Systems.**

Comment: *EPA Should Account for Recent Data on Emissions From Power Plants and Refineries*.
A recent paper published in the journal Environmental Science & Technology used the aircraft mass balance approach to estimate methane emissions at three refineries and three natural gas power plants (NGPP) in the U.S.15 Measured emission rates were 21–20 and 11–90 times higher than reported to the GHGRP for NGPPs and refineries, respectively. The authors scale up emissions by throughput to estimate that these two sources contribute 610±180 Gg CH4 in the U.S., which is about 20 times higher than the estimate in the GHGI. Although this estimate is based on a small dataset, it suggests that the GHGRP and GHGI greatly underestimate emissions from these sources. EPA should evaluate this study and other data sources to increase the accuracy of their emission estimates for refineries and NGPPs.

Response: As noted in the Planned Improvements section of 3.5 Petroleum Systems and 3.6 Natural Gas Systems, EPA continues to seek new data that could be used to update or assess the estimates in the Inventory.

Comment: *The Inventory Underestimates Emissions from Superemitters*. Superemitters are relatively infrequent, large emission sources that result from malfunctions or abnormal process conditions. A recent meta-analysis found that superemitters are ubiquitous across the oil and gas supply chain with a general rule of the top 5% of sources accounting for 50% of total emissions.16 The Draft 2017 GHGI partially accounts for superemitters by including emissions from the Aliso Canyon storage facility well blowout and production sector stuck separator dump valves.

Although the partial inclusion of superemitters is a step in the right direction, the current approach nonetheless greatly underestimates emissions from these sources. For instance, in addition to Aliso Canyon, there are many other superemitters in the transmission and storage sector (T&S). Zimmerle et al. estimates that T&S superemitters were responsible for 353 Gg CH4 emissions in 2012.17 For the final 2017 GHGI, we recommend that EPA use Zimmerle et al. to estimate emissions from T&S superemitters in addition to including the emission estimate from the Aliso Canyon blowout.

Response: **EPA will continue to assess studies that include and compare both top-down and bottom-up estimates and could lead to improved understanding (e.g., identification of emission sources and information on frequency of high emitters) of unassigned high emitters or "super emitters," as recommended in stakeholder comments. See the Planned Improvements sections in 3.5 Petroleum Systems and 3.6 Natural Gas Systems.**

Comment: For the production sector, the Draft 2017 GHGI incorporates emission estimates from stuck separator dump valves in their revised methodology for storage tank. As discussed in our feedback on the Production Memo, we have concerns that the underlying GHGRP data used to estimate stuck dump valve emissions greatly underestimates their emissions due to a flawed calculation methodology. In brief, the GHGRP method assumes that tank emissions are approximately 3–4 times higher than normal flashing emissions during stuck dump valve conditions, but in reality, emissions can be several orders of magnitude higher up to the entire natural gas production of a well. Additionally, production superemitters may include other causes such as poorly operating separators or malfunctioning pressure relief valves.

Response: **Data reported to EPA's GHGRP undergo a multi-step verification process, as discussed in the QA/QC and Verification section of the 3.6 Natural Gas Systems and 3.5 Petroleum Systems. As noted in the Planned Improvements section of 3.5 Petroleum Systems and 3.6 Natural Gas Systems, EPA continues to seek new data that could be used to update or assess the estimates in the Inventory.**

Comment: In addition to these specific sources, we generally recommend that EPA evaluate other approaches for estimating superemitter emissions, such as top-down and bottom-up comparisons of basin-level emissions. For example, a recent study estimated that one-third of site-level well pad emissions in the Barnett Shale could not be attributed to component-level emissions and were likely caused by superemitters resulting from abnormal process conditions or otherwise avoidable emissions.18 In context, the Draft 2017 GHGI estimate of stuck dump valves only accounts for 0.2% of production emissions. For future inventories, it is critical that EPA fully account for superemitters since these sources may account for a substantial portion of total oil and gas supply chain emissions and likely counteract the downward revisions made to other sources.

Response: **EPA will continue to assess studies that include and compare both top-down and bottom-up estimates and could lead to improved understanding (e.g., identification of emission sources and information on frequency of high emitters) of unassigned high emitters or "super emitters," as recommended in stakeholder comments. See the Planned Improvements sections in 3.5 Petroleum Systems and 3.6 Natural Gas Systems.**

Commenter: Environmental Interface Limited

John Cowan

Comment: My concern relates to EPA's accounting for the generation of the CO2 exported by pipeline from North Dakota as part of a Carbon Capture and Storage system. I note on page 3-27, lines 1-3, that EPA states, "Since this CO2 is not emitted to the atmosphere in the United States, energy used to produce this CO2 is subtracted from energy consumption statistics." Though this same statement was accepted by the ERT in 2011, it strikes me as incomplete because it does not identify what constitutes the energy used to produce the CO2. I presume you do not actually subtract all of the fossil fuel used in the generation of CO2, since that would mean the CO2 not captured at the site is ignored, though it is clearly a US emission.

Also your statement relates to the energy used to "produce" the CO2. Creation of the CO2 from fossil fuel combustion is only part of what it takes to produce the CO2 for export. So your "produce" statement implies that the energy used for capturing the CO2 (e.g. for scrubbing, liquefaction, pumping) is also subtracted, even though the energy is probably in the form of electricity. Such methodology departs from the principle of assigning emissions to their sources. If this principal is to be broken, then why couldn't the energy used to create exported electricity (or exported anything) be ignored in the inventory?

So presuming you subtract only the fraction of the fossil fuel representing the recovered fraction of the CO2, a more clear statement about this would be: Since this CO2 is not emitted to the atmosphere in the United States, the associated fossil fuel burned to create the exported CO2 is subtracted from fossil fuel consumption statistics. The associated fossil fuel is the total fossil fuel burned at the plant with the CO2 capture system multiplied by the fraction of the plant's total site-generated CO2 that is recovered by the capture system.

Response: **EPA agrees with the characterization of how the adjustment for CO_2 export was made. It only reflects the C in the CO_2 exported, not C in fuels used to produce the CO_2. The language in the Inventory report was adjusted to reflect this comment.**

Commenter: Federal Highway Administration

John Davies

Comment: Table ES-3, p. ES-11: Given the increased penetration of battery electric and plug-in hybrid vehicles, it's surprising to see a reported decline in transportation electricity CO2 emissions (down about 10 percent between 2014 and 2015, and down over 20 percent between 2005 and 2015). The Electric Drive Transportation Association estimates cumulative U.S. sales of about 400,000 light-duty vehicles by the end of 2015, up from nearly zero vehicles in 2010. See http://electricdrive.org/index.php?ht=d%2Fsp%2Fi%2F20952%2Fpid%2F20952. See also Transportation Energy Data Book Edition35 Table 6.2 (2010 to 2015 sales).

Response: **Consistent with previous Inventory reports, the current Inventory accounts for the electricity used to charge electric vehicles primarily in the residential and commercial sectors. Therefore, higher electric vehicle market penetration rates would not increase the reported transportation sector CO_2 emissions. As a planned improvement, EPA will look into the possibility of breaking out electricity used to charge electric vehicles and reporting that electricity use under the transportation sector. See Section 3.1 Planned Improvements for more information.**

Comment: Table 2-13: As noted in footnote 7, FHWA changed its methodology to apportion on-road and non-road gasoline consumption in its Highway Statistics 2015 document, so applying the published on-road / non-road ratios from Highway Statistics is causing a noticeable discontinuity in the Inventory's estimates between 2015 and earlier years, especially for on-road transportation. It is suggested that the 2015 on-road / non-road ratio be applied retrospectively to estimate on-road gasoline consumption for 2014 and earlier years.

Response: **As noted by the commenter, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which resulted in a break in the time series between 2015 and previous years in the allocation of gasoline among transportation and other sectors in the current Inventory. EPA plans to conduct further research to better understand FHWA's method update and to evaluate and potentially update the method for allocating gasoline across sectors to improve accuracy and create a more consistent time series in future versions of the Inventory report. See Section 3.1 Planned Improvements for more information.**

Comment: Table 2-13: If the Inventory estimates are adjusted to reflect an increase in on-road gasoline GHG emissions, it would be worth noting that this trend has been significantly influence by the recent growth in light-duty VMT. Following a period of stagnation (lasting from 2009 to about 2013), light-duty increased by 1.6 percent from 2013-2014, and 2.5 percent from 2014 to 2015 (see 2014 and 2015 Highway Statistics Table VM-1).

Response: **Annex 3.2 of the Inventory report includes information on vehicle miles traveled (VMT) by vehicle type and fuel type (see Tables A-96 through Table A-98) as well as estimates of VMT**

distribution by vehicle age and vehicle class. More information on recent VMT trends were also incorporated into Section 2.2 and Section 3.1 of the Inventory report.

Comment: Table 2-13: Suggest including an italicized line item at the bottom of the table showing biofuel CO2 emissions, as is done for Table 2-4.

Response: **Table 2-13 has been updated to include biofuels.**

Comment: p. 3-19: Might also note the recent VMT trends, especially the accelerating growth in 2015 and 2015 mentioned above.

Response: **Annex 3.2 of the Inventory report includes information on VMT by vehicle type and fuel type (see Tables A-96 through Table A-98) as well as estimates of VMT distribution by vehicle age and vehicle class. More information on recent VMT trends were also incorporated into Section 2.2 and Section 3.1 of the Inventory report.**

Comment: Figure 3-13: Orange line should be labeled % passenger cars.

Response: **Figure 3-13 has been updated**.

Comment: Table 3-12, italicized line item: Suggest including biodiesel and labeling this biofuels.

Response: **Table 3-12 has been updated to include biofuels.**

Commenter: Ford Foundation

Penny Davies

Comment: I note the potential for improvement in the forest carbon reservoir and stock, which, in the light of current political trends, might be something worth highlighting.

Response: **As noted in the Planned Improvements section of the *Forest Land Remaining Forest Land* chapter, efforts are underway to improve the ability to estimate carbon stock and stock change for forest lands.**

Comment: As an addendum, it is interesting that Scotland, a place close to President-elect's heart, recently published its climate action plan (reported by the BBC), and the Scottish parliament's debate of it, and Scotland's new target of reducing greenhouse gas emissions by 66% by 2032. They agreed to assign budget to it. It was criticized, however, for not including enough on the need for cuts in emissions from the transport sector, insufficient was made about the potential positive role of the forest sector, and not enough was made of incentives to encourage behavioral change.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Ford Foundation

David Kaimowitz

Comment: I believe that the EPA has done a good job with this draft inventory. It is good to see how a consistent concerted effort has gradually improved the quality of these reports, which are essential for the future of the planet. We at the Ford Foundation regularly use these inventories, as well as inventories from other countries for our own work and analysis. We certainly hope that the EPA continues to invest in improving these reports.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: George Washington University (GWU) Environmental and Energy Management Institute (EEMI)

Joseph Cascio

Comment: First, let me thank EPA for their continued commitment to meet its UNFCCC treaty obligations to submit and publish annual GHG inventory reports. These are both extremely valuable and necessary to continue progress on GHG mitigation and adaptation. The U.S. can be proud of its contributions for leading the development of new and improved methodologies for estimating emissions and sinks, both of which are used widely by domestic audiences, as well as by the international community. In academia, U.S. GHG data is necessary to educate students on trends and on the scope of the issues to be addressed.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Comment: Is there any ready explanation of how electricity imports from Canada are accounted for?

Response: **The Inventory focuses on emissions occurring in the United States. Therefore, emissions from electricity production are based on energy used to produce electricity in the United States. The data come from fuel consumption data for U.S. electricity production provided by EIA. Emissions from producing electricity imported into the United States are accounted for in the country in which the electricity was produced**.

Commenter: Greenhouse Gas (GHG) Management Institute

Michael Gillenwater

Comment: On behalf of the Greenhouse Gas Management Institute, I want to thank the USEPA on their ongoing work to rigorously quantify and publicly report emissions and removals of greenhouse gas (GHG) emissions from the United States. Since President George H.W. Bush signed the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, the United States has dutifully fulfilled its treaty commitment to preparing an annual inventory of GHG emissions and removals. The GHG inventory program at the USEPA has been an international leader in developing good practice for this scientific process. Specifically, many of the methodologies encoded in the international guidelines published by the Intergovernmental Panel on Climate Change (IPCC) got their start through technical work lead by the USEPA.

This 2017 report, specifically, presents valuable developments in the integration of facility level data from the GHG Mandatory Reporting Program as well as important technical work to better understand methane emissions from the petroleum and natural gas industries. The USEPA GHG inventory program has always upheld a strong standard for scientific rigor and unbiased analysis. Many government programs, including those operating within the USEPA itself, would like to have their activities featured and promoted in the U.S. inventory. Yet, over the 20 years of annual reporting, USEPA's GHG inventory program has always focused on unbiased technical rigor, while also striving to inform both the technical community and public at large with clear data and insightful analysis.

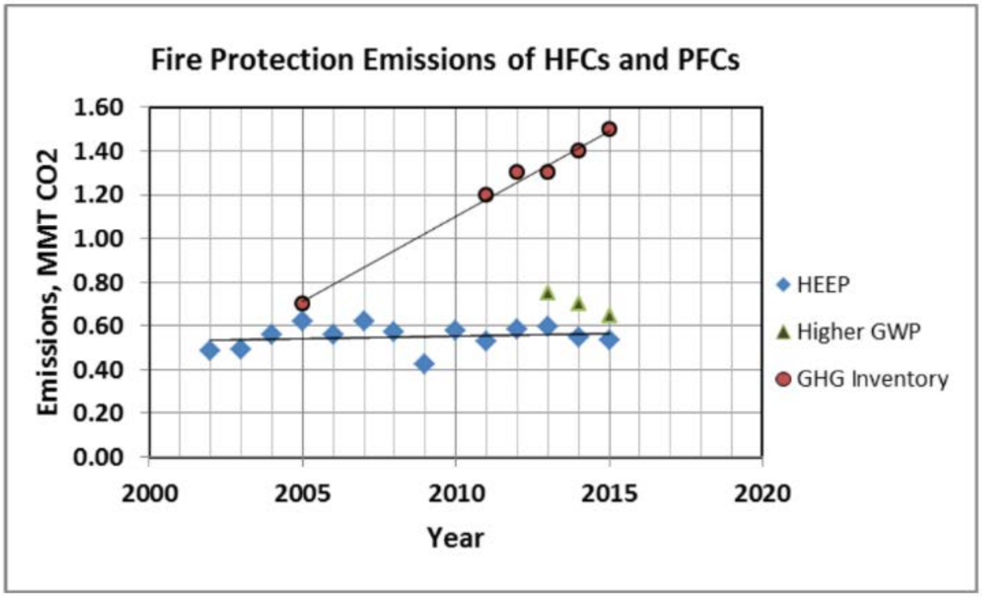
Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Halon Alternatives Research Corporation, Inc. (HARC)

Thomas Cortina

Comment: *Comparison of HEEP data and U.S. GHG inventory data on fire protection***.** The HFC Emissions Estimating Program (HEEP), conducted by HARC, is a companion to the Voluntary Code of Practice for the Reduction of HFC & PFC Fire Protection Agents (VCOP) that provides a format to help industry minimize emissions by setting benchmarks, by providing the incentives to make improvements to current standards and practices, by documenting the industry's commitment to safety and responsible use, and by providing data to support the goals of the VCOP. HEEP collects data on sales of HFCs and PFCs used for recharge of fire protection systems and extinguishers as a surrogate for emissions. Compiled data of estimated emissions is submitted to EPA and published each year.

Enclosed is the most recent HEEP report, which shows that between 2002 and 2015 annual emissions of HFC and PFC fire protection agents averaged 0.550 MMTCO2. HARC acknowledges that there is some potential leakage in the program from recharge agents that are directly recycled by users and systems that discharge and are never recharged, however, we believe the data reflects close to 90% of the U.S. fire protection industry's actual emissions. Since 2002 the HEEP data has been calculated using GWPs from the 2nd IPCC Assessment Report. The draft U.S. GHG inventory uses GWPs from the 4th IPCC Assessment Report that are higher for all of agents measured under HEEP. We recalculated the HEEP data for 2013-2015 using the 4th Assessment Report GWPs and the values increased by between 21-28%. For the most recent year, 2015, the adjusted HEEP value was 0.643 MMTCO2 while the draft U.S. GHG inventory value for fire protection was 1.5 MMTCO2. Overall the fourteen-year HEEP trend line suggests that the reported emissions have been stable over the measurement period. When the HEEP program began in 2002, the expectation was that emissions of HFCs from fire protection would continue to increase each year as the size of the installed base grew. This expectation is reflected in the draft U.S. GHG inventory, which shows a 114% increase in HFC emissions from fire protection between 2005 and 2015. Instead what the HEEP data show are essentially invariant emissions of GHGs over the 2002 through 2015 period. Below is a graph of the HEEP and draft U.S. GHG inventory data that illustrates these differences.



HARC attributes the invariance of fire industry emissions to steadily improved stewardship of installed systems by owners and the high level of recycling of halogenated clean agents. When the HEEP program began in 2002 about 13% of the reported HFCs sold for recharge came from recyclers. In recent years this number has ranged from 70-80% and in 2015 it reached a high of 84%. At a time when EPA is promulgating regulations to increase recycling of HFCs in other sectors, the fire protection industry has achieved this high level of recycling without a regulatory mandate.

HARC has provided input to EPA in recent years on the vintaging model that provides the basis for the data on emissions of fire protection agents presented in the draft GHG inventory. Based on our previous review of the model's assumptions, we believe that the vintaging model may not accurately account for the return of recycled agent to the market for recharge, and that this may contribute to the model's predictions of steadily increasing emissions. HARC has been invited by ICF to participate in a peer review of the EPA vintaging model and hopes to contribute to making improvements in the model's accuracy that might be reflected in future inventories.

***Response:* EPA looks forward to working with the commenter to understand the following specific issues related to improving these estimates:**

- **Emission estimates from the segment of the fire protection industry not reporting to HEEP;**
- **Emission estimates of HFCs and PFCs disaggregated by chemical species;**
- **Whether emission rates in EPA's Vintaging Model over the time series are too high, which are currently consistent with the *IPCC Guidelines*;**
- **Whether growth rates in EPA's Vintaging Model for streaming agents and total flooding agents are too high and which available resources can inform more accurate growth estimates; and**
- **Whether EPA's Vintaging Model methodology is somehow not accounting for the recycling described in the comments.**

Commenter: Integrated Sustainability Solutions LLC

Keith Forbes

Comment: For the last 25 years or so, EPA has been a leader in GHG inventory methodologies. I authored the LULUCF chapter of the EIA (DOE) GHG inventory for the U.S. for 7 years using data from the EPA and USDA/USFS, so am intimately familiar with the guidelines. EPA's methodologies have been widely adopted and integrated into IPCC guidelines for GHG inventories for all countries. EPA methods have also been used by numerous state and voluntary registries in the U.S. and elsewhere, as well as for private sector GHG reduction efforts by numerous corporations. Therefore, it is critical that EPA inventory methodologies remain based upon the best science and are transparent. Thank you for the opportunity to comment.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Ionia Farm

Jane Fisher

Comment: I just quickly want to say how incredibly important the EPA is and cannot imagine in a time like this, with so much environmental destruction and environmental health problems, etc that the EPA (budget, staff, goals) is at risk. Thank you for doing what you are doing for all of us and of course for many generations to come.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: National Council for Air and Stream Improvement, Inc. (NCASI)

Brad Upton

Comment: EPA characterizes production of the pulp and paper sector as the sum of wood pulp production plus paper and paperboard production, based on data from the Food and Agriculture Organization of the United Nations (FAO). Summing wood pulp, paper, and paperboard production results in double counting, because the majority of wood pulp production is used to produce paper and paperboard at integrated mills (an integrated mill includes both pulping and papermaking at the same facility, with a single wastewater treatment system). Therefore, production statistics used by EPA to represent the pulp and paper sector are too high. As we have suggested before, a more appropriate method for characterizing total pulp and paper sector production would be to sum paper production, paperboard production, and market pulp production. The American Forest and Paper Association (AF&PA) publishes this information annually in its Statistical Summary reports, which are submitted each year to the US Library of Congress.

Average Outflow. EPA characterizes wastewater generation per ton of production based on water discharge statistics from AF&PA Sustainability Reports. These are the most current and relevant data for this characterization, and NCASI submits no comments on this use other than to emphasize that the agency should ensure it is using the most current version of the report.

Organic Loading in the Outflow. EPA characterizes the organic load in untreated wastewater using a legacy value of 0.4 gram BOD per liter of untreated effluent and a multiplier of 2 to convert from BOD to COD. NCASI has very limited data on untreated effluent organic load. Therefore, until additional data are available, we cannot suggest an alternative value.

In summary, use of FAO statistics overstates the pulp and paper industrial sector's production by double counting pulp used to produce paper and board at integrated mills, which in turn results in estimates of pulp and paper sector industrial wastewater treatment methane emissions being far too high. EPA should use production data from AF&PA's Statistical Summary reports to avoid this double counting. This will result in more accurate characterization of industrial wastewater treatment methane emissions from this sector.

Response: **As stated in past Inventory reports and in the Planned Improvements section for Wastewater Treatment of the current 1990 through 2015 Inventory, EPA is working with the National Council of Air and Stream Improvement (NCASI) to determine if there are sufficient data available to update the estimates of organic loading in pulp and paper wastewaters treated on site. These data include the estimates of wastewater generated per unit of production, the BOD and/or COD concentration of these wastewaters, and the industry-level production basis used in the Inventory. Data on the industry-level production basis to date has been received and will be incorporated, but in order to incorporate that data, the production basis in relation to the wastewater generation rate and the organic content of the wastewater needs to be evaluated to ensure it is incorporated correctly into the Inventory. Based on NCASI's recommendation in these comments, the *2016 American Forest & Paper Association Sustainability Report* will be evaluated to ensure the most current wastewater generation rate for the pulp and paper industry is used in the Inventory.**

Comment: A new component of this draft inventory is the inclusion of drained organic soils on forest land. The approach identifies planted forests on mesic or xeric sites (based on forest inventory plot data) that coincide with organic soils (according to spatial soil datasets). The result (70.85 k ha) is multiplied by a simple emissions factor to obtain the annual flux. However, this approach does not distinguish between permanent "deep drainage" and shallow, temporary alteration to surface hydrology (such as bedding), which is widely implemented in the US South to establish forest regeneration. Nor does it use forest age to accommodate changing emissions rates with time since drainage. We encourage EPA and USDA Forest Service to work towards continual refinement and improvement of this estimation approach, perhaps moving to a Tier II estimate, although the flux remains small relative to other components of the inventory.

Response: **This is the first year the Inventory Team has estimated emissions from drained organic forest soils. EPA will continue to explore data sources and approaches to move from the Tier I approach implemented in the current Inventory to more country-specific estimates in the years ahead.**

Commenter: The Nature Conservancy

Lynn Scarlett

Comment: The Nature Conservancy applauds the Environmental Protection Agency for its leadership and science-based approach in producing consistent annual greenhouse gas inventory reports going back to 1998 that allow us to understand trends across every sector of the economy, including the contribution to climate change mitigation made by carbon sequestration in our forests and lands. The latest of these is the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015. Transparent accounting for our GHG emissions and sinks is a critical part of the solution to protect our environment and prudently manage the risks presented by climate change. A rigorous, science-based greenhouse gas inventory is the foundation for evaluating and undertaking prudent actions to manage the very significant risks posed by climate change to our society and economy. The U.S. has long been a leader in the transparency and comprehensiveness with which it reports on its greenhouse gas emissions, and we are pleased to see that continuing here. It has done so by applying basic scientific principles of data collection: transparency, accuracy, completeness, consistency and comparability.

EPA works with every industry to do the best possible job of characterizing their emissions, and regularly updates the estimation models for each industry based on the best available science. The effort over the last few years to refine methane emissions from oil and gas emissions reporting – even in the face of controversial debates over fracking – is a good example. It is worth noting that no industry has advanced a concerted attack on EPA estimates for its emissions.
The greenhouse gas inventory is also an important part of ensuring that countries transparently report their emissions under the UN Framework Convention on Climate Change. By implementing a rigorous, science-based approach to our inventory, the U.S. sets an important model for other countries to follow and improve their own reporting. Indeed, U.S. assistance to help other countries improve their data collection and reporting capacity has been an important complement to our own inventory process, enhancing overall global transparency. We also appreciate the EPA's efforts to draw upon in this latest draft inventory the information and proposed guidance from recent IPCC special reports, including the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. As one of the first countries to implement this guidance, the United States has demonstrated leadership in advancing the understanding and importance of the relationship between these vital ecosystems and climate change solutions.

The United States thoughtfully spends millions each year to monitor a wide variety of potential security and public health threats, such as flu strains in wide circulation, microbes resistant to antibiotics and viruses on the Internet that may shut down our electric grid. Carefully measuring greenhouse gas emissions and their sources is part of this same effort to protect our health, jobs and environment from threats that can alter our environment and cripple our economy in ways that have the potential to cause untold damage. In sum, the inventory is a critical part of a responsible science-based insurance policy to avoid devastating impacts on the physical systems of our planet that we could not have anticipated if we failed to collect the data. We welcome this Draft Inventory, and applaud EPA and its partner agencies for their efforts to produce it.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Portland Cement Association

Michael Schon

Comment: *Request for Revision of EPA Estimation Method Used to Calculate the Cement Industry's Process Emissions*. In this year's Draft Inventory, EPA estimates the process emissions from cement manufacturing using the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines. See Draft Inventory at 4-8. Those guidelines are scheduled for refinement in 2019 and are no longer the best method for estimating process related emissions from cement manufacturing. The World Business Council for Sustainable Development (WBCSD) issued Version 3.0 of its report titled "CO2 and Energy Accounting and Reporting Standard for the Cement Industry" (WBCSD Report) in May 2011 (This report is available at http://www.wbcsdcement.org/pdf/tf1_co2%20protocol%20v3.pdf). The WBCSD Report shows that the B1 Method (described in the report) can be used to estimate process related emissions from cement manufacturing, based on clinker production, in a manner which addresses certain limitations of the 2006 IPCC Guidelines. The B1 Method is therefore more accurate than what appears in the IPCC Guidelines. See WBCSD Report at 15-17 & App'x 3.

Of note, the B1 Method accounts for the CO_2 emissions resulting from both organic material and magnesium carbonate in the raw material, while the IPCC method does not. The difference is significant. The base emission factor in the IPCC Guidelines is 0.507 tons of CO2 per ton of clinker while the updated default WBCSD factor is higher, at 0.525, plus an upward adjustment for organic material in the kiln feed. We recommend that the EPA re-calculate the process emissions from cement manufacturing considering this WBCSD method. PCA would welcome the opportunity to facilitate further dialogue between PCA, EPA, and the WBCSD on the specifics of this issue.

***Response*: Please refer to Planned Improvements discussion in section 4.1 Cement Production of the Inventory Report, where EPA references engaging with PCA to review the current emission factor and the basis and applicability of the WBCSD method and default factors to U.S. clinker production processes, to refine the current country-specific emission factor used to estimate CO_2 emissions from clinker production for future Inventory reports in order to better account for other components of raw kiln feed.**

Comment: *Request for EPA Inclusion of Carbonation as a Sink*. While the Draft Inventory accounts for process emissions that are emitted when cement is manufactured, the Draft Inventory does not occur for the carbonation that occurs later in cement products' life cycle. Cement products in-use, post-demolition, and post-recycling reabsorb atmospheric CO_2 over time because of a physiochemical process called carbonation (*See, e.g.,* Fengming Xi, et al., "Substantial global carbon intake by cement carbonation," *Nature Geoscience* (2016), http://www.nature.com/ngeo/journal/v9/n12/full/ngeo2840.html). The significant sink of carbonation is not discussed in the 2006 IPCC Guidelines. EPA should refine its Draft Inventory to account for this sink. Again, PCA would welcome the opportunity to discuss this request in further detail.

***Response:* Please see the Planned Improvements discussion in section 4.1 Cement Production of the Inventory report for additional information regarding EPA's planned efforts to address this long-term improvement.**

Commenter: Rhodium Group

Kate Larsen

Comment: The GHG inventory is an extremely useful document and dataset that we use on a regular basis in providing analysis that informs our clients' corporate and policy decision-making. We have come to rely on the regular public release of this data and on EPA's engagement with academia and industry experts in the field to improve methodologies over time. I look forward to seeing the final 2017 Inventory in April.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: Trakref

Ted Atwood

Comment: *Emissions from CFCs and HCFCs should be included in the Inventory*. Fluorocarbons (CFCs, HCFCs, and HFCs) continue to dominate the market share in the United States. In fact, in 2015, approximately 462 million pounds of fluorocarbon refrigerants were consumed in the United States, and that number is expected to rise to approximately 508 million pounds in 2020 (Markets and Markets 2015). Above all, when looking at the U.S. refrigerant market size, an important factor is that the leak rate in the United States has averaged ~25% of the share growth in the market, and neither CFCs nor HCFCs are excluded from the outlook.

Yet, Section 1 of the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015 (hereby referred to as Inventory) does not include usage emissions from CFCs and HCFCs, even though these are two of the most prominent greenhouse gases (GHGs) with significant ozone depleting potential (ODP) and global warming potential (GWP). Section 1.1 attempts to provide an explanation for their exclusion: "As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in national greenhouse gas inventories." Though including CFCs and HCFCs may not be "required," this does not discount their emissions and their significant impact. Excluding them from the Inventory misrepresents our GHG emissions and means that we are without a clear view of the total GHG inventory. This is where the discrepancy with the refrigerant numbers originates. Thus, the following is argued: 1) the emissions from CFCs and HCFCs should be included in the Inventory and 2) fluorocarbon emissions (CFCs, HCFCs, and HFCs) are undercounted across the board, particularly when factoring in reclaim rates, equipment sales, and leak rates. The former shall be explained with a case example of HCFC-22 usage; the latter shall be explained with an overview of market consumption.

First, Section 4.13 of the Inventory details HCFC-22 Production in the United States, particularly the emissions of its byproduct, HFC-23. In fact, it states, "In 2008 and 2009, U.S. production declined markedly and has remained near 2009 levels since." It goes on to describe a "long-term decrease in the [HFC-23] emission rate" and explains that this is in large part due to the decline in production of HCFC-22. However, principally, a decline in production does not equate to a decline in market demand (as evidenced by the stockpiles consumed amid the phaseout). Nowhere in this Section 4.13 is there a mention of a decline in market demand of HCFC-22. In the Final Rule for HCFC Allowances in 2015-2019 published in October 2014, the EPA concluded “that there is still significant servicing need for HCFC-22.”(1) Yet, the consumption of HCFC-22—which is millions of pounds annually—for servicing equipment currently in use has been disregarded in the Inventory. What ends are achieved by doing this? The fact that this particular fluorocarbon refrigerant, HCFC-22, is under a phaseout is secondary, what is primary and most important is the fact that this refrigerant is one of the most commonly used refrigerant and also has a very high GWP that of 1,760. When you take the widespread use of this refrigerant and its high-GWP coupled with the national leak rate average of 25%, that translates to significant emissions into the atmosphere, not to mention reclaim rates of R-22 have been less than expected and recent news reports of a possible impending R-22 shortage (i.e., supply demand imbalance) indicate significant venting of R-22 has occurred. This case example with R- 22 is not an anomaly but rather a symptom of the much larger problem: The undercounting of fluorocarbon emissions.

Response: **As indicated by the commenter, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are not required to include emissions from CFCs and HCFCs in national greenhouse gas inventories, as these gases are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. Therefore, the United States does not include emissions from CFCs and HCFCs in Table 4-94 of the Inventory. However, emission estimates of CFCs and HCFCs are summarized in Table A-295 of Annex 6.2 Ozone Depleting Substance Emissions.**

Comment: *Fluorocarbon emissions (CFCs, HCFCs, and HFCs) are Under-counted*. Additionally, if we look to Section 4.23, the problem only enlarges. Specifically, the Section states that 168.6 MT Co2e was emitted from HFCs and PFCs in 2015, and it was the refrigeration and air-conditioning sector that “contributed the most towards emissions of HFCs and PFCs … in 2015 (144.9 MMT CO2e, or approximately 86 percent).” While this number (i.e., 144.9 MMT CO2e from refrigeration and air conditioning) is much too low (and this will be explained momentarily), it should be noted that it does go on to state that “these refrigerants are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at servicing and disposal event.” Thus, HFC emissions from usage and servicing—not just manufacturing (as with HCFC emissions discussed in the preceding paragraph)—are acknowledged. However, despite this acknowledgement, there is still an underreporting of HFC emissions in regards to refrigeration and air-conditioning (144.9 MT CO2e) occurring, which, of course, translates into the HFC and PFC total emission number of 168.6 MT CO2e being too low as well. Let me explain further.

As stated previously, in 2015, approximately 462 million pounds of fluorocarbon refrigerants were consumed in the United States. This consumption number for 2015 alone indicates that the emissions are much more than what is reflected in the Inventory. For instance, take this approximation: Essentially, we have 462 million pounds of refrigerant, attributed to HFCs and HCFCs. Assuming a 1 to 1 correlation between pounds and MMT CO2e, we have an estimated 462 million MT CO2e. Now, 18 million MT CO2e of R-22 was allocated for 2015. By deducting 18 million MT CO2e of R-22 from 462 million MT CO2e, that leaves 444 million MT CO2e. So, in sum, the assumption is 444 million MT CO2e from supply and market activity. Now, let’s deduct the following from that number: 145 million MT CO2e for HFC emissions from the Inventory report; 32 million MT Co2e for installation into new equipment (i.e., using a 7% growth rate, which is higher than the actual 4% growth rate in 2015(4), 3 million MT CO2e for destruction, 0 for reclaim (although 10 million pounds recovered, it is assumed they were resold and vented, and the 18 million MT CO2e for HCFCs/CFCs. Once these deductions have been subtracted from the 444 million MT CO2e, that leaves 246 million MT CO2e unaccounted for—This is the discrepancy. If we add this 246 number to the approximate 145 million MT CO2e found in Table 4-96 of Section 4.23, we get 391 million MT CO2e—In other words, that's our determination of the approximate amount being vented into the atmosphere for 2015 alone. That's staggering (and we haven't even included any assumptions about those numbers in regards to stockpiles). Accordingly, we estimate that for the years 1990 through 2015 nearly 8 billion pounds of F-gas have been vented into the atmosphere. However, the emissions reporting found in the Inventory is not based on venting but rather on a complex tailing report to 65 critical use paths for F-gas, which is essentially demand reporting.

Here's the crux: What does it matter if we consume 462 million pounds of fluorocarbon refrigerants, if there is only one end life: venting? As an illustration, only 1% of all fluorocarbon refrigerants are properly destructed at the end of their lives; the other 99% end up vented into the atmosphere, as there is no destruction requirement for these compounds. With this in mind, it's important to point out: Demand reporting is in conflict with traditional EPA controls. For good reason, EPA doesn't have resources to adequately capture the complex nature of inventory movements in each vertical of consumption space. So naturally, if EPA is using supply controls to manage F-gas phaseout, then we should follow the same path in reporting. That means accounting for consumption through service deployment, through leak emissions and then replacement, etc. Consequently, further research needs to be conducted to determine the actual values of F-gas inventory from a supply perspective—not a demand perspective—so that the EPA can reasonably and accurately calculate it without having to survey industries for their consumption. Importantly, there is one major indication that service ultimately leads to venting: the case of SF6 reporting through the EPA's own Facility Level Information on Greenhouse gases Tool (FLIGHT). Indeed, consumer emissions from SF6 are reported. Therefore, we see and document SF6 usage and their emissions value, but we have no such value for all F-gas refrigerants currently. So, to reiterate, the 391 million MT CO2e of F-gas vented in 2015 is off-the-books. And think of this: if we were to include SF6 emissions into our approximation of the total amount of F-gas vented, that 391 million MT CO2e number would only increase.

As shown above, F-gas emissions are grossly undercounted for, and unless the described reporting issues are addressed and rectified, we will most likely, and unfortunately, continue on this same path: Venting millions of pounds of F-gas without any visibility to the real impact that it has to the bottom line for carbon accounting.

Response: **IPCC guidance (Volume 3, Chapter 7 of the *2006 Guidelines for National Greenhouse Gas Inventories*) indicates that it is not good practice to equate emissions with consumption (i.e., the amount of virgin chemical produced or imported annually in the country minus the amount of chemical destroyed or exported in the year of consideration) as this method does not take into account accumulation or possible delayed release of chemicals in various products and equipment. As explained in the Inventory, estimates of emissions of ozone depleting substance substitutes are from a "bottom-up" model that tracks equipment sales rather than a "top-down" method which would start with chemical sales and reclamation rates as discussed by the commenter. Rather than the commenter's assumption that each pound of fluorinated greenhouse gas is exactly one metric ton of carbon dioxide equivalent, specific Global Warming Potentials (GWPs) are applied to each chemical. See Annex 6.1 of the Inventory report for more information on GWPs. Emissions of sulfur hexafluoride (SF_6) are discussed in Chapter 4 of the Inventory report in sections 4.19, 4.22 and 4.24. These estimates are included in the estimates of total U.S. greenhouse gas emissions.**

Commenter: U.S. Geological Survey

Hendrik G. van Oss

Comment: *"Global Warming Potential" Nomenclature*. In the Ch. 1 Introduction, I was struck by the EPA's adoption of the phrase "Global Warming Potential" (Sec. 1, p. 8) for the title of the table of GHG equivalences. I would urge the EPA to use a less prejudicial phrase. Popular as this phrase may be, it is not well-grounded in science.

Logically, a global warming potential of a GHG ought to be cast in terms of °C/ton or even °C/ton-year, but the units instead are given as tons of CO2e (equivalents), where CO2 itself is defined as 1. This, then, forces the user to rely on whatever warming is ascribed to CO2 by this or that model, over some specified time frame. There is no well-defined global warming potential for a single ton of CO2; the argument is made that XXX zillion tons of anthropogenic releases of CO2 over ZZ years has led to a Y°C increase in average world temperature over that which was occurring naturally (post-Little Ice Age etc...). How long does it take 1 ton of CO2 to begin to have an effect? There are a vast number of variables; the models dealing with these require supercomputers, and come up with different answers. And none of these models have much to go on re. dealing with most of the other GHGs.

Regarding CO2 itself, one cannot, of course, define a °C/ton relationship, and one does not know the destiny of a specific ton of emitted CO2--it may be sucked up by the nearest forest, get absorbed into the ocean, stay in the lower atmosphere, etc...etc.... All of this is poorly constrained. Thus, the EPA should STICK TO WHAT YOU KNOW. The relative (vs. CO2) heat retentions of the various GHGs can be demonstrated in the lab under controlled conditions--this is what you know!--although different studies come up with somewhat different equivalences, as your table shows. What you don't know is the effect, real or potential, of these various gases on the climate; the lab is NOT the global climate. The assumption is made that all the GHGs remain in the atmosphere (long-term) and are uniformly mixed therein, and that there are essentially no sinks--all of which are dubious, especially for some of the more exotic GHGs. I would thus urge the EPA to drop the phrase "Global Warming Potentials" and instead provide the same data under non-prejudicial phrasing such as: Greenhouse Gas Equivalences or Greenhouse Gas Heat Retention Equivalences. And then you can use straightforward phrasing such as "..emissions of CO2 and CH4 (in terms of CO2- equivalents)......" You can measure (or calculate reasonably well) the emissions, right now, this year, next year... The emissions are what you know.

***Response*: See also Annex 6.1 of the Inventory report. Global Warming Potential (GWP) is intended as a quantified measure of the *globally averaged relative radiative forcing impacts* of a particular greenhouse gas. It is defined as the cumulative radiative forcing–both direct and indirect effects–integrated over a specific period of time from the emission of a unit mass of gas relative to some reference gas (*Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*). Carbon dioxide (CO_2) was chosen as this reference gas. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. GWP values allow policy makers to compare the impacts of emissions and reductions of different gases.**

More information on global warming potential and other metrics for comparing different emissions can be found in the IPCC *Fifth Assessment Report (AR5), Working Group I: The Physical Science Basis*.

Comment: *Cement Production.* I looked also at the Ch. 4 Industrial Processes & Product Use, most closely at the section on Cement (I developed the cement methodology for the IPCC). I have a few minor quibbles: Table 1-4 and in the cement section (Sec. 4, p. 3): the USGS has yet to publish a (Minerals Yearbook--MYB) production number for clinker for 2015, but the USGS monthly reporting (December 2016 edition) now shows USA (including Puerto Rico) production of clinker = 76,603,356 mt; if past MYB reporting is a guide, the MYB number for 2015 will be very close to this number (because I allow no more than a 5,000 short ton/year difference for a specific plant's monthly vs. annual reporting and most agree within a few tons). Where larger (> 5,000 st) discrepancies are found, I ask the companies to review their data, and usually some revisions are then forthcoming. This comparison and revisions to 2015 data have been ongoing throughout 2016, and with the December 2016 monthly report, the final monthly data for 2015 are provided. Unfortunately, we are still missing nearly 20 annual forms for the 2015 survey as of 3/16/2017, so I do not know when the 2015 MYB tables will be available. Anyway, this new monthly data total for 2015 would yield process emissions of 39.9 Mt CO2, using the 0.5101 EF and a CKD adjustment of 2% (i.e., clinker x 0.5101 x 1.02), not the 39,587 kmt/39.6 Mt CO2 figure that you give (which was based on a now obsolete clinker number). Monthly data for 2016, by the way, show a small (1.22%) decline for 2016 vs. 2015, but the 2016 data remain subject to revision for the next 12 months. The 2016 decline was a surprise--our 2017 Mineral Commodity Summaries had a small estimated increase for 2016, as indeed was indicated at the time of its writing (data in hand at that time were for 1-8/2016, I believe).

Response: **The latest data provided by USGS and published in early March 2017 is integrated into the Inventory report. In addition, this year EPA integrated clinker production data from EPA's GHGRP (Part 98) into the time series for 2014 and 2015. Updated USGS data were used as QC for 2014 and 2015; see Table 4-4 on p. 4-10. Consistent with previous Inventory reports, EPA will update historical data and recalculate emissions with final publications of USGS data (for 1990 to 2013) for the next Inventory and will continue to use more recent years for comparison. EPA plans to continue regular engagement with the USGS commodity expert on clinker production values as EPA compiles the next Inventory report. Please also refer to the Methodology and Recalculations Discussion sections in section 4.1 Cement Production for more information on the data utilized in estimating 2015 emissions.**

Comment: Line 4-5: please refer to the USGS as the U.S. Geological Survey **National Minerals** Information Center. You have a slightly different wording.

Response: **This change has been made in the Inventory diagram on p. 1-12.**

Comment: On line 7 your wording (as to what goes on in the kiln) is slightly misleading--you need to describe the calcination reaction as (from a GHG process emissions perspective) as being the key reaction (current wording makes it sound like a lime kiln). The equation given ($CaCO3 + heat = CaO + CO2$) is correct, but this reaction takes place in the temperature range of about 700 - 1000°C, not 1450°C. The 1450°C is the temperature that the raw materials are then (post-calcination) taken to so as to achieve a reasonable rate of formation of the alite mineral phase (C3S in shorthand via the reaction C2S (belite) + C = C3S, where C = CaO and S = SiO2)--this is the so-called sintering phase of clinker formation, and includes partial melting. Alite starts to form at 1338°C, but because there is only slight melting at that temperature, the reaction is very slow; given practical residence times in the kiln, they take the temperature higher (to 1450°) so as to have 20-30% melting, which speeds the reaction significantly. But, the sintering reaction has essentially no effect on process emissions.

Although the emissions from fuel combustion are, of course, dealt with in a separate section, some mention of them should be made because clinker manufacture is highly heat-intensive. The fuel combustion emissions will, however, depend on the kiln technology (re-use of heat, hence less fuel; use of a precalciner) and the type of fuels. What likely is not estimated adequately are emissions from burning of waste fuels (the data are poor), and the contribution of kerogen in the raw materials (as well as any other carbon, such as graphite, or soot in, say, fly ash) fed into the kiln.

If we are using a wet kiln, the 30-40% slurry water will first need to be evaporated (c. 1.8 GJ/ton clinker), the nowdry raw material mix needs to be raised to calcination temperatures (i.e, preheating), which is another ~ 1.8 GJ/ton clinker, then the calcination is done while raising the temperature to about 1000°C (yet another 1.8 GJ/t), and then the sintering is done (to 1450°C)--which only adds ~ 0.2 GJ/t because the alite-forming reaction noted above is highly exothermic. Anyway, depending on the technology, a lot of fuel gets burned to provide this heat--typically 150-200 kg of coal or similar per ton of clinker. So the process emissions are only about half the story!

Response: **The change regarding the description of the calcination reaction process has been made in the Inventory report. With regard to combustion emissions, note the first sentence of section 4.1 states that *"*Emissions from fuels consumed for energy purposes during the production of cement are accounted for in the Energy chapter."**

Comment: Line 16: you earlier describe clinker as being 65% CaO (all from CaCO3) and quote me as saying that this is reasonable (which it is). You should thus adjust the EFclinker derivation equation to use the CaO factor of 0.65 and NOT 0.6460. The latter number is inherited from older summaries, and derives from a straight arithmetic average of a few sample clinker analyses given on an old cement chemistry book--it is too precise. We can justify an average of 65%, but cannot justify 64.60%. Using the rounded CaO content of 0.65 changes the derived EF clinker to 0.5101 t CO2/t clinker (and then we multiply this by 1.02 to given a token accounting for "lost" CKD).

Response: **This change has been made in the Inventory report, see section 4.1 of Chapter 4.**

Comment*: Other Process Uses of Carbonates*. Other carbonate use: you show a CO2 fraction of limestone of 0.43971--this implies that the limestone is 100% CaCO3, which it will almost never be. I'd round it to something more like 0.43 (= 98% CaCO3), or deduct a couple of percent from the calculated CO2 to better represent an actual high-purity limestone.

Response: **This change has been made in the Inventory report, see section 4.4 of Chapter 4.**

Comment: *Iron and Steel*. Page 4-60, line 9-2--I noted a statement along the lines of "...62% of U.S. steel was produced in one of seven States..." -- I think you meant to say: "...62% of steel produced in the USA was from seven States..." (I do not believe that 1 of these 7 did 62%...). I did not have time to review the iron and steel section very thoroughly.

Response: **This change has been made in the Inventory report, see section 4.16 of Chapter 4.**

Comment: **Blast Furnace and Steel Furnace Slags.** One issue not addressed, and as the Fe slag specialist at the USGS, I cannot actually answer, is the possibility that there is a small carbon content of blast furnace and steel furnace slags--either as a minor component of the silicate slag phases or as a modest component of any entrained metal. Perhaps one of your steel company specialists can address this possibility. All of my books on slag have chemical analyses that make no mention of carbon. But because we would, in the carbon balance of the blast furnace, deduct c. 4-5% C in the crude (or pig) iron (although most of this will be subsequently burned off in the steel furnace), there is a possibility that some elemental C gets caught up in the slag (possibly as entrained kish or even within entrained crude iron).

Response: **EPA will consider this comment in making future improvements, pending review of literature to understand and address this possibility.**

Commenter: University of Virginia

Deborah Lawrence

Comment: Thank you for all the work that went into the inventory of US GHG emissions and sinks. Without this knowledge, we cannot begin to contemplate effective action to limit climate change. Without this knowledge, we cannot honor our obligations to the UNFCCC, and more importantly, to the most vulnerable on this planet and to future generations. Thank you for all you do.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Comment: I would like EPA to take a closer look at the way they account for emissions and sinks in the land use sector. Being from the southeast, I am very concerned that much of the apparent 'timber' extraction is actually much more like 'pulp' extraction in its effects. Wood is being removed to create wood pellets, not to create long-lived carbon sinks in houses. Wood pellets go straight back into the atmosphere within the year. Very different fate from wood that is actually made into timber.

Response: **The Forest Inventory and Analysis (FIA) program captures harvest removals, but those are not attributed to a particular product or use. Furthermore, there is a lag in the removals within the FIA program and there are other sources that provide more timely estimates that have historically been used in the WoodCarb II model used for the Inventory of Harvested Wood Products (HWPs) estimates. The Inventory team intends to use Timber Products Output data from the FIA program (https://www.fia.fs.fed.us/program-features/tpo/) in the years ahead as EPA moves towards an annual, design-based sampling framework which will provide more timely information useful in assessing product use and appropriately tracking emissions and removals from HWPs.**

Comment: In general, I would like to see EPA account for biofuels more fully—especially when they come from forests. Wood-based biofuels are not carbon-neutral. Burn wood, emit CO2—and emit more CO2 per BTU of energy than many fossil fuels. I'd like to see EPA account for that.

Response: **EPA has added accounting of biodiesel used in the transportation sector to Section 3.10 of the Inventory report for more transparency.**

Commenter: Waste Management, Republic Services, National Waste & Recycling Association, Solid Waste Association of North America, SCS Engineers, and Weaver Consulting Group

Kerry Kelly

Comment: *The Inventory of U.S. Greenhouse Gas Emissions and Sinks is a valuable and necessary data source.* The U.S. Greenhouse Gas (GHG) inventory is a credible data source, rather than a policy document, and provides important information, based on sound and transparent methods for many public and private stakeholders. The landfill sector relies on the U.S. GHG inventory for variety of purposes. These include tracking GHG emission trends at the national and state levels, in total and by sector (e.g., waste), and by source category (e.g., MSW landfills). Because the inventory covers the six major greenhouse gases – carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride – GHG-specific trends in emissions can also be developed at the national and state levels, in total, and by sector, source category. This information is important to private companies seeking to compare their emissions performance to national trends, and to educate customers and communities. The information is also important to public sector waste officials to educate the public and to make more informed decisions about solid waste management planning.

Other stakeholders, including states rely on the U.S. GHG Inventory as a model for developing their GHG emissions data. The inventory data are used in policymaking contexts by Federal agencies, state governments, corporations and trade associations, and non-governmental organizations. In addition, the data are used by investment firms, academics, companies and many others seeking information on GHG emission trends. Scientists also use the GHG inventory data to develop atmospheric models and to compare airplane or satellite emissions monitoring to the GHG inventory's bottom-up approach.

The U.S. GHG inventory provides useful and detailed data on GHG emissions in the United States across many sectors. Since EPA began preparing the U.S. GHG inventory in the early 1990s, the Agency has refined the GHG inventory in several important ways. First, in addition to calculating the emissions each year, EPA also quantifies uncertainties for all source categories, implements quality assurance and quality control, and updates new methodological approaches as needed. Second, over the years the GHG inventory development process has been improved to incorporate significant stakeholder input and transparency. Specifically, EPA has added two opportunities for comment – one for technical experts and the other for the public.

EPA has engaged with industry stakeholders concerned about emission levels, methodological approaches, or other topics related to their sector emissions. In fact, the landfill sector raised such concerns over the last year, and we appreciate EPA's efforts to understand and improve the methodology used to quantify MSW landfill emissions.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Comment: *We support EPA's use of net CH4 emissions from the GHGRP.* We strongly support EPA's decision to use landfill-specific emissions data from the GHGRP in the Inventory as we conclude it is more reliable and accurate data for estimating emissions from MSW landfills. In previous comments on this issue, we explained why using GHGRP data is the preferred approach.

The MSW landfill sector (Subpart HH) emissions data are significantly more detailed and up-to-date than the estimation approach used in previous GHG Inventories;

Every MSW landfill reporting to Subpart HH is subject to annual validation via EPA review of submitted data – a level of scrutiny that does not occur in the GHG Inventory;

Each MSW landfill that reports under Subpart HH has a “designated representative,” who must certify – under penalty of law – that the data submitted by the site are accurate and developed in accordance with regulatory requirements.

These data provide a more detailed and accurate approach to emissions quantification for the majority of U.S. MSW landfills. Subpart HH data elements include historical and current waste disposal quantities by year, CH4 generation, gas collection system details, CH4 recovery, CH4 oxidation, and CH4 emissions, and thus, are considered “Tier 3” (the highest quality) data under the IPCC Guidelines.

The landfill sector recognizes that the new methodology uses both the first-order decay model and back-casting methods. We agree with EPA’s approach of (1) using the actual GHGRP data for years 2010 to 2015; (2) back-casting emissions based on overlap between the GHGRP and the FOD model for the years 2005 to 2009; and (3) using the FOD model with some updates for the years 1990 to 2004. It is our view that this approach leverages the GHGRP data in a useful way, while also recognizing that an over-reliance on GHGRP data in the early years of whole time-series could create uncertainty.

We also agree with EPA’s decision to rely on Environmental Research and Education Foundation (EREF) reports on waste disposal, which are to be published every three years. As EPA notes, “data were extrapolated for 2014 and 2015 based on national population growth because no data are available from these sources [State of Garbage (SOG) or EREF] for those years. Upon publication of the next EREF report, the waste landfilled for 2014 to the current Inventory year will be updated.” (U.S. EPA, Draft U.S. Inventory, Annex 3.14, p. 393)

Response: **EPA appreciates the commenter’s support of the methodology changes to the MSW landfill emissions calculations in the 1990-2015 Inventory.**

Comment: *Applying a scale-up factor to the GHGRP data.* Recognizing that the GHGRP does not include every landfill in the country – small landfills and industrial landfills do not report to the GHGRP – we support EPA’s decision to use a scale up factor to estimate emissions from non-reporting landfills. In the current U.S. Inventory, EPA has applied a scale-up factor of 12.5 percent to cover the non-reporting landfills, and the Agency also states “this scale-up factor may be revised in future years after a thorough review of available data for the non-reporting landfills is completed” (p.7-11). We are concerned that the scale-up factor of 12.5 may be high, and remind the Agency that we recommended that a scale-up factor of 10.0 would be sufficiently conservative to avoid underestimating emissions. We thus urge EPA to move expeditiously in reviewing emission estimates for non-reporting GHGRP landfills.

Response**: As stated in the Planned Improvements of Section 7.1 Landfills of the 1990 through 2015 Inventory, EPA will continue to investigate the annual waste disposal quantity for landfills not reporting to EPA’s GHGRP and engage with stakeholders to develop a more precise scale-up factor to**

apply to the GHGRP data. The LMOP database, WBJ database, and other datasets will be reviewed against the GHGRP waste disposal data.

Comment: *We support the Agency recalculating MSW generation and disposal data and CH4 generation estimates for the years 1990 to 2004.* For the period 1990 to 2004, EPA is relying "on the previous methodology, … whereby a disposal factor is applied to nationwide, annual MSW generation amounts."4 Based on a recent EREF report, "the MSW generation data were modified for the years 1990 – 2013 to reflect recently published data and to align with how MSW quantities are applied under Subpart HH of the GHGRP to estimate CH4 generation." 5 Specifically, EPA revised earlier SOG survey data "to exclude construction and demolition waste and inert materials from the annual quantities of waste generated used in the first order decay model."6 SOG surveys are available for 2002, 2004, 2006, 2008, 2010, and 2013, and EPA used these data to extrapolate MSW generation for the years 1990 and 2001, and to interpolate for 2003. The landfill sector supports this methodological approach, as the data show a relatively consistent downward trend, which contrasts with the initial trend line in the Draft Inventory for 1990 – 2014, where CH4 emissions began increasing around 2002.

Response: **EPA appreciates the commenter's support of the methodology changes to the MSW landfill emissions calculations in the 1990 through 2015 Inventory.**

Comment: *The Agency's Merging methodologies for time series consistency appear appropriate.* We have concluded that EPA used the IPCC's methodologies for time series consistency in an appropriate manner. We note that EPA used the "overlap" method during the period when the previous method and the new method could both be applied (e.g., 2010 to 2015), and used the back-cast method, based on the trend lines in 2010 to 2015 data, to estimate CH4 emissions from 2005 to 2009. Finally, EPA applied its previous method to estimate CH4 emissions from 1990 to 2004, with certain modifications described in the previous section. Overall, we find that EPA's revised approach to the MSW Landfill category of the GHG Inventory is much improved, and we appreciate EPA's efforts to update the GHG Inventory estimation methodologies.

Response: **EPA appreciates the commenter's support of the methodology changes to the MSW landfill emissions calculations in the 1990 through 2015 Inventory.**

Comment: *EPA's Planned Improvements.* As noted previously, EPA is planning to investigate annual waste disposal quantity for landfills that do not report under GHGRP Subpart HH. In addition, EPA "will also investigate options to adjust the oxidation factor for those non-reporting landfills from the default 10 percent currently used, to another value such as those included in the EPA's GHGRP." The landfill sector strongly supports EPA's plan to adjust the oxidation factor from 10 percent. We note, however, that EPA appears to be considering the use of "another factor" for non-reporting landfills. To the extent most non-reporting landfills are likely to be small, old, or both, we urge EPA to apply appropriate factors to different types of landfills, based on the range of oxidation factors provided in Subpart HH.

Response: **As stated in the Planned Improvements of Section 7.1 Landfills of the 1990 through 2015 Inventory, EPA will investigate options to adjust the oxidation factor from 10 percent currently used, to another value such as those included in EPA's GHGRP.**

Comment: *We support EPA's decision to use the oxidation factors currently being used in Subpart HH for the years 2005 to 2015 and change oxidation factors in the 1990 – 2004.* It also appears that EPA has decided to revise the long-standing approach of using 10 percent oxidation for all landfills based on the following statement in Annex 3.14:

> Results from this research consistently point to higher cover soil methane oxidation rates than the 2006 IPCC Guidelines default of 10 percent. A continued effort will be made to review the peer-reviewed literature to better understand how climate, cover type, and gas recovery influence the rate of oxidation at active and closed landfills. At this time, the IPCC recommended oxidation factor will continue to be used for all landfills for the years 1990 to 2004. (emphasis added)

We support EPA's decision to use the oxidation factors currently being used in Subpart HH for the years 2005 to 2015. Further, it seems reasonable to change oxidation factors in the 1990 – 2004, as the non-reporting facilities are largely old small closed landfills with final cover material compatible with RCRA Subtitle D requirements, which took effect May 1991.

Response: **As stated in the Planned Improvements of Section 7.1 Landfills of the 1990 through 2015 Inventory, EPA will review peer-reviewed literature to determine options for updating the oxidation factor to better reflect oxidation rates for the years 1990 to 2004.**

Comment: *We urge EPA to make additional enhancements in next year's inventory, particularly with respect to the DOC factor and Lo.* EPA should review and incorporate updated DOC values, based on EREF's research. As noted in our previous comments related to key revisions in the Draft Inventory for 1990 – 2015, we urge EPA to develop updated DOC values, based on research provided by EREF. We recommend that EPA acknowledge that the long-standing default DOC values are obsolete and initiate a process to update them. Per EREF:

> "The implicit assumption with a guideline value … is that the types and proportion of MSW materials, both degradable and inert, is relatively constant and uniform. If the proportions of either degradable or inert waste materials going into a landfill changes, the fraction used in the DOC calculation may also change and potentially result in a different DOC value. In such instances, the DOC guidelines would yield estimates of landfill gas emissions that are less representative of real-world conditions. An additional complicating factor in the use of a single representative DOC value as a guideline is that, in addition to MSW, MSWLFs in most states may accept one or more non-MSW Subtitle D wastes (Staley, B.F. and D.L. Kantner, Environmental Research and Education Foundation (EREF), "Estimating Degradable Carbon in MSW Landfills and the Impact of Non-MSW Materials," 2015, p. 2).

As EREF has explained to EPA during the recent MSW landfill stakeholder process, for MSW-only landfills, EREF's analysis found that "an average DOCMSW of 0.184 was computed from the state study data, with values ranging from 0.142 - .209 (p. 6)" A default value of 0.2028 is the DOC value currently used in the CH4 generation estimates from MSW-only landfills. EREF also analyzed non-MSW materials going into MSWLFs, and notes that "Given a third of incoming waste to MSWLFs consists of non-MSW materials, there is significant potential for non-MSW materials to impact the relative fraction of organics and degradable organic carbon (DOC) of the MSWLF waste stream" (p. 9).

Based on this analysis, EREF concludes: The average computed DOC value for MSW waste using state data was 0.184, or roughly three-fifths of the MSW guideline value. The average computed DOC value for bulk waste using state data was 0.161, or roughly four-fifths of the bulk waste guideline. This analysis suggests that the U.S. EPA's guideline DOC values of 0.31 for MSW-only landfills and 0.20 for facilities accepting non-MSW Subtitle D wastes overestimate DOC at these landfills and, as a result, may result in inaccurate estimate of landfill gas generation and methane emissions (p. 13).

We recognize that EPA has not yet engaged in updating the DOC, Lo, and k values, and we also note that EPA has determined that "a value of 100 m3/Mg appears to be a reasonable best estimate to use in the FOD model for the national Inventory for years 1990 through 2004, and is the value used to derive the DOC value of 0.2028" (US EPA, Draft US GHG Inventory p. A-395). At the same time, we strongly urge EPA to begin updating the DOC default values next year, focusing on the years 2004 to 2015. EREF's research shows that changes in the waste stream disposed in landfills over the last decade – specifically, the decline in organics and the increase in non-MSW waste in MSW landfills – have led to DOC values that are lower than in previous years. Based on EREF's more recent research, particularly with respect to the decline in organic waste going into landfills, we recommend that EPA to review the information available in the GHGRP to determine whether data in that dataset would be more useful. Presuming that Subpart HH contains the necessary data elements, it may be possible for EPA to develop a more scientifically sound approach to updating the DOC values, which would rely on significantly more landfills.

Response: **As stated in the Planned Improvements of Section 7.1 Landfills of the 1990 through 2015 Inventory, EPA will continue to review the DOC value used in the first order decay model, review peer-reviewed literature, and engage with stakeholders to determine options for updating it, as appropriate.**

Commenter: Water Environment Federation

Patrick Dube

Comment: Change "sewage sludge" to "biosolids" throughout the document to be more in line with EPA's own preferred nomenclature.

Response: **This change has been made in the Inventory report.**

Comment: Page 6-47 Line 17 - The land application of biosolids have been shown to significantly increase soil organic carbon.

Response: **EPA agrees with the commenter that land application of biosolids can increase the organic carbon contents of soils. While biosolids are not specifically mentioned on page 6-47, lines 17 through 19 of the draft Inventory report, biosolids would be considered as an "organic amendment," and a carbon input. Currently, biosolids are only considered to be applied to Grasslands as EPA does not have data that would allow us to distinguish between application to different land uses. See page 6-66 in the final Inventory report under the heading "Additional Mineral C Stock Change Calculations" for information on how biosolids are currently treated in estimating soil carbon stock changes.**

Comment: Page 6-66 Line 22-23 - In regard to the line "Cropland is not likely to be amended with sewage sludge due to the high metal content and other pollutants in human waste": Biosolids are safe to be land applied to cropland when following EPA’s federal biosolids rule 40 CFR Part 503. Part 503 rule limits the amount of metals, pathogens and dioxins that can be applied while also outlining a process for crop harvesting, record keeping and reporting standards. The proper land application of biosolids can increase crop growth and yield while reducing fertilizer costs and improving soil health.

***Response*: This line has been edited in the final Inventory report to state: Although biosolids can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in Grassland Remaining Grassland.**

Comment: Page 7-32 Line 11 - Replace ‘www.wef.org/biosolids’ with the more direct link ‘http://www.resourcerecoverydata.org/’

***Response:* This change has been made in the Inventory report.**

Commenter: A. Aoki

Private Citizen

Comment: I am writing (as a non-scientist) to voice my support for the Draft GHGI and EPA's continuing work in documenting greenhouse gas emissions. We need to keep these kinds of records so that our society has accurate information on both greenhouse gases and how to reduce emissions. This data is needed to protect our public health and well-being, our food and water security, and our economic growth. Without the EPA’s work on the GHGI and the public availability of data, scientists will find it harder to develop atmospheric models. Policy makers will not be able to make science-based decisions about emissions policies or know if the policies are working. Regulatory agencies and corporations won’t have a way to establish and measure compliance with emissions policies. Businesses, the public, and interest groups will be uninformed about greenhouse gases.

***Response:* EPA appreciates the commenter’s support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: L. Aoki

Private Citizen

Comment: I am writing to voice my support for the EPA's work in documenting greenhouse gas sources and sinks in the United States. We need to sustain this record of US emissions so that our society has accurate information on both greenhouse gas emissions and efforts to reduce those emissions. By making this inventory publicly available, the EPA provides an invaluable service to policymakers at all levels of government, to leaders in industry and business, and to individual citizens. Climate change is a threat to all Americans - to our public health and wellbeing, our food and water security, and our economic growth. EPA should continue this critical work on the greenhouse gas inventory so that we have the knowledge we need to move forward in addressing climate change.

***Response:* EPA appreciates the commenter’s support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: S. Aoki

Private Citizen

Comment: This is a valuable report that provides data on a natural source/sink and industry-by-industry basis in a consistent format. It is particularly important to have validated longitudinal series for future scientific and economic analysis.

***Response:* EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: B. Chadwick

Private Citizen

Comment: page 2-10: "The remaining 18 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure 2-5 and Figure 2-6)": Add the '2015 U.S. Energy Consumption by Energy Source' pie chart (e.g. Figure ES-12 on page ES-19) to show all categories of energy sources. Figure 2-5 and Figure 2-6 are incorrectly referenced for this statement. Add a statement to the introductory paragraph about what is presented in Figures 2-5 and Figure 2-6.

***Response:* The text was adjusted to reflect the figures being referenced. EPA will consider further edits to respond to this comment in future versions of the Inventory.**

Comment: page 3-7: Figure 3-4: "U.S. Energy Consumption (Quadrillion Btu)": (1) change the scale of the y axis to provide more detail; (2) add gridlines so that energy consumption can be read more easily from the graph; (3) It appears that data for energy consumption + consumption of fossil fuels for non-energy use have been graphed with a peak of about 100 qBtu in 2007. From my estimates, using fossil fuel energy data provided in Table A-18 of EPA's draft Inventory and nuclear and renewable energy provided in the EIA's MER, total energy consumption in 2007 peaked at about 93 qBtu.

***Response:* The values in Figure 3-4 have been updated to reflect the values used in the final release of the Inventory report. EPA will consider further edits to the Figure 3-4 to add clarity. According to Table 1.3 of EIA's MER, total primary energy consumption was greater than 100 QBtu in 2007.**

Comment: pages ES-19 and 2-10: "In 2015, approximately 82 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels...": From my estimates, in 2015, total fossil fuel energy in the US (not including US Territories) amounted to 71.8219 qBtu (using data in Table A-11 of the EPA's Inventory Annexes). Nuclear and renewable energy (including geothermal energy) and imported electricity amounted to 18.014 qBtu (using data in EIA's February 2017 Monthly Energy Review, Tables 1.3 and 2.6). So fossil fuel energy was about 80% of total energy consumed in 2015.

Response: **Table A-11 in the Inventory report is adjusted to account for non-energy uses. Just using EIA MER data for 2015 in Table 1.1, fossil energy accounted for 81 percent of total energy consumption.**

Comment: page 2-10 and 3-1: Figures 2-5, 3-1: "2015 Energy Chapter Greenhouse Gas Sources (MMT CO2 Eq.)": The scale of the bar chart deemphasizes the significance of fossil fuel combustion:- Shorten the "bar titles" so that the bar representing "fossil fuel combustion" can be lengthened.
Redoing the adjacent piecharts of these figures, to show "fossil fuel combustion emissions" as a percent of total US greenhouse gas emissions (5,049 MMTCO2 Eq. is 77% of 6,586.2 MMTCO2 Eq) would help readers see why climate change policy should be centered on reducing fossil fuel consumption.

Response: **EPA will consider edits to respond to this comment in future versions of the Inventory.**

Comment: page 2-3: "Energy-related CO2 emissions also depend on the type of fuel or energy consumed and its C intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO2 emissions because of the lower C content of natural gas": Explain that the carbon intensity of an energy mix is the energy-weighted average of the CO2 emission factors of all energy sources in the mix including carbon-free/neutral energy sources. Provide a table of CO2 emission factors for all energy sources including nuclear and renewable energy and/or refer readers to Table A-39: "Key Assumptions for Estimating CO2 Emissions" in the Annexes to the Inventory with an explanation on how to convert "carbon content coefficients" to "CO2 emission factors". Describe the decarbonization of the US electric power sector between 2005 and 2015, as done on page 3-14.

Response: **A reference to Table A-39 was added to the text. A discussion of the decarbonization of the electric power sector was added to the Energy portion of the Trends chapter**.

Comment: page ES-12 : (a) "Recently, a decrease in the carbon intensity of fuels consumed to generate electricity has occurred due to a decrease in coal consumption, and increased natural gas consumption and other generation sources. Including all electricity generation modes, electricity generators used natural gas for approximately 33 percent of their total energy requirements in 2015": Clarify the decarbonization of the primary energy consumed to generate electricity (qBtu) (e.g. 37% coal; 36% nuclear and renewable; 26% natural gas; 1% oil products in 2015) and/or the electricity generated (kWh) (e.g. 34% coal; 33% nuclear and renewable; 32% natural gas; 1% oil products in 2015) with a breakdown of energy groups in the mix and provide a piechart.

Response: **A discussion of the decarbonization of the electric power sector was added to the Inventory report, including a figure showing relative contribution of different energy sources and emission trends.**

Commenter: K. Grote

Private Citizen

Comment: Thank you for the EPA's continued commitment to meet its UNFCC treaty obligations for submitting and publishing annual GHG inventory reports. I also appreciate that the USA has been a leading developer of new and improved methodologies for estimating emissions and sinks, which are used widely by domestic audiences and the international community. In my two previous roles at Pacific

Gas and Electric Company and at EOS Climate, Inc., I relied heavily on GHG estimation methods in my work. At PG&E, I was working with local governments in the San Francisco Bay Area to reduce their greenhouse gas emissions. All of our community inventories relied heavily on your GHG estimation methodologies. At EOS Climate, we sought to develop new environmental commodities traded on blockchain technology. Again, our accounting methodologies relied heavily on your work.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: A. Haber

Private Citizen

Comment: I am writing in support of continued work on the national Greenhouse Gas Inventory. I greatly appreciate that your agency does this work, and that it is publicly available. The continuance of data on US GHG emissions is non-partisan, and will benefit everyone nationally as well as globally. In addition to ensuring the well-being of our planet, this is critical for public health and food security.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: M. Horn

Private Citizen

Comment: Thank you for your ongoing commitment to meeting UNFCCC treaty obligations for reporting and publishing annual GHG inventory reports. As an American living overseas, I'm proud the USA has been a leader in developing new and improved methodologies for estimating emissions and sinks that have gained acceptance at home and serve as a model overseas. GHG estimation methods and U.S. GHG data is important for enabling global GHG emission management. If the quality of those data are compromised, it would cause enormous headaches later when much of the world moves to a CO2 emission "budget" regime, as proposed in IPCC assessment review V. It would be a nightmare if US data has to be adjusted in the future because quality issues such as tinkering, discrepancies, and gaps come to light that require "margins of safety" to be added to ensure US emissions remain on budget. Let's not move backwards now! The world is watching.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Comment: I'm especially concerned about fugitive methane leaks at the well head in hydraulic fracturing. As reduced emission completions (green completions) were phased in by the Obama administration in consultation with the American Petroleum Institute, I thought the industry had realized upholding this standard was in its best interest but the Trump administration seeks to roll them back at API's bequest. This would be a major setback and likely make the task of accounting for methane emissions from fracking even harder and uncertain.

Response: **Methane emissions from hydraulic fracturing (HF) completions and workovers are included in the Inventory for both natural gas and petroleum systems. For natural gas systems, EPA calculates national HF completion and workover emissions using data from EPA's GHGRP on completions and workovers that vent without controls, that flare, that use RECs and that use both RECs and flaring. For petroleum systems, EPA calculates national HF completion and workover emissions using data from DrillingInfo on gas production from oil wells, assumptions on duration of completion and workover events, and an estimated flaring rate. EPA will review upcoming data from the GHGRP on hydraulically fractured oil well completions and workovers, available in 2017 for the first time, for potential updates to the Inventory.**

Commenter: P. Lawrence

Private Citizen

Comment: I cannot see any issue more important than climate change. We must have data to deal with that. Hence there is a desperate need for the relevant data gathering which the EPA is in charge of. It is of utmost importance that this data inventory continue with the funds necessary to maintain it.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: M. Macrae

Private Citizen

Comment: I would like to thank the EPA for their continued commitment to meet is UNFCCC treaty obligations for submitting and publishing annual GHG inventory reports. The USA has been a leading developer of new and improved methodologies for estimating emissions and sinks, which are then used widely by domestic audiences and the international community. This data helps support institutions such as Harvard in evaluating their own carbon footprint and developing adaptation and resiliency planning. Please continue this effort.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: R. Palomaki

Private Citizen

Comment: I am writing to express my support for continued EPA funding for programs like the Greenhouse Gas Inventory. As the most powerful nation on Earth, the United States has a duty to be a global leader in combating climate change. We can only continue to serve in this role with sufficient funding to agencies like the EPA. Reports like the GHG Inventory will ensure that our scientists, and indeed scientists across the globe, are provided with up-to-date, factual evidence about greenhouse gas emissions and the effects that those emissions have on our atmosphere. Climate change is not a partisan issue. The effects of greenhouse gas emissions will cross all political, racial, and class divides.

We owe it to future generations to continue this research and do all in our power to reverse the trends already in motion.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: C. Ridenour

Private Citizen

Comment: Thank you for the inventory of US GHG emissions. The inventory is critical to let industry and others know how we are doing – and to live up to our commitments to the world community. Working hard on understanding sources and sinks is critical, and as a US forest owner, I am always especially interested in the methods for measuring sequestration from forests. Transparency is key.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: F. Seymour

Private Citizen

Comment: I write to express my appreciation for the EPA's work on producing an inventory of US GHG emissions and sinks, and for making the report available for public review. I work on international forest and climate policy, and the USG attention to producing such reporting, and undertaking public consultation, is both essential for US leadership on climate change, and useful for modelling best practices for other countries. I do not have detailed comment on the report itself, but am grateful to have been offered the opportunity.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: C. Tingley

Private Citizen

Comment: I find this inventory valuable. It is only by tracking this inventory over time that we can determine how we are doing. Climate change is the greatest existential threat to the United States and we must remain on focus to address it.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Commenter: J. Venezia

Private Citizen

Comment: Thank EPA for your continued commitment to meet UNFCCC treaty obligations for submitting and publishing annual GHG inventory reports. The USA has been a leading developer of new and improved methodologies for estimating emissions and sinks, which are then used widely by domestic audiences and the international community. I use GHG estimation methods and U.S. GHG data all the time in my work and analysis, helping my clients do carbon footprinting and looking for ways to reduce their GHG emissions.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

Comments Received during the Public Review Period on the "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008."

Reviewer: Bill Allen

General Comment

Comment: *It's cooling and temperatures are below the levels of the 1930s! CO_2 is not causing warming! Collecting data on "greenhouse" emissions is a total waste of tax payer money! CO_2 is required for life to exist on this planet and the more we have the better is for all plant life.*

Comment: *We don't need to be wasting taxpayer money on collecting data on green house gases! This is a surface temperature measurement for Yemassee, SC and as you can see, temperatures have declined since the 1930s; 1934 is officially the hottest year on record in the US. You should be aware of the "urban heating effect" which causes surface temperatures in urban areas to be warmer due to the effects of human activities. The temperatures in downtown large cities are as much as 8 degrees warmer than the surrounding rural areas! There is absolutely no reason to regulate CO_2!*

Comment: *The attachment shows how the temperature data shows a warming bias due to the urban heat effect. The first graph shows the temperature much closer to what it really has been, with the hottest years in the 30s.* [See Appendix A for additional details.]

Reviewer: Francis Jeffrey & Janine Gonsenhauser, Circular Sea [TM] Consulatants

Annex 5: Assessment of the Sources and Sinks of Greenhouse Gas Emissions Excluded

Comment: *We wish to point out that in the section, Annex 5 (PDF) (6 pp, 180K) - Assessment of the Sources and Sinks of Greenhouse Gas Emissions Excluded, the treatment of the Ocean in the category of "non-anthropogenic" effects, or as indeterminate, may be very misleading. By our own science-based estimates, the Ocean system provides an annual net sink of about 10Gt [CO_2], of which about 5Gt [CO_2] is recycled into oxygen returned to the atmosphere. The former figure is in positive relationship with (chiefly) the CO_2 concentration of the atmosphere (now around 388 ppm [by volume], versus some 280 ppm pre-industrially). The latter figure (ie, 5Gt.) is in positive relationship with the health and productivity of the ocean, on average, which has declined about 20% over the same time-frame (as quantified by the statistic called "NPP" -- cf: the Panetta and Watkins committees, for assessments of recent decline.) The United States is largest national source of influences upon both Ocean sink figures, the former (directly) via net CO_2 emissions, and the latter (indirectly and inversely) via water pollution; consequently the changes in these statistics are properly anthropogenic effects, which are on the same order of magnitude as the figures themselves, when considered on decadenal time-scales. (In addition, decreases and degradations of marine biomass may amount to net and cumulative emissions of greenhouse gasses, and the cumulative absorption of un-recycled CO_2 in the Ocean amounts to* *acidification which modifies the physical environment adversely for beneficial biota and carbon-sequestering components [such as the carbonate capsids of some phytoplankton, for example].)*

Reviewer: Giles Ragsdale

Executive Summary

***Comment**: Given the recent contentious events related to climate change data manipulation, exactly how far back and how often is "recent" historical data updated (per the Executive Summary)?*

***Comment**: Overall an increase of 14% is noted in the total US emissions. Has any thought been given to at least noting the rate of CO_2 emissions/Net emissions on a per capita basis year over year in order to provide some context related to the US population increase and whether emissions are trending up or down per capita?*

Trends

***Comment**: A comparison is made between 2007 and 2008. Why is no mention made that the 2008 MTCO2eq total is also lower than 2005, 2006, as well as 2007 and is the lowest since 2000? Ditto for the totals for Fossil Fuel Combustion and overall Net Emissions, etc. There are circumstances but these trends seems significant and noteworthy.*

Reviewer: Bernard Kutter

General Comment

***Comment**: It is time for America to take responsibility for our actions. America has caused the vast majority of the Worlds atmospheric increase in CO_2 and other green house gasses. The results are already affecting the world in the form of increased ocean acidity killing corals, melting of glaciers, changing weather patterns. We will always have the excuse that reducing our emissions is too hard, that it will cost too much, that the developing world should reduce their emissions. The reality is that America can reduce our emissions while simultaneously enhancing our long term economic prospects. Indigenously produced wind turbines, solar, geothermal and nuclear combined can reduce our emissions to levels well below 1990. Please put strong curbs on the allowed emissions of CO_2 and other green house gases.*

Reviewer: Eric Johnson

General Comment

***Comment**: The U.S. Environmental Protection Agency's work on the 2010 Draft U.S Greenhouse Gas Inventory is excellent. This will provide an important reference for evaluating environmental impacts of greenhouse gas emissions and for identifying priority areas for reducing greenhouse gas emissions.   The tables and figures on greenhouse gas emissions by economic sector and trends in greenhouse gas emissions are very useful. This document establishes important benchmarks for comparison with other nations and to evaluate the* *effectiveness of future greenhouse gas reduction efforts. Thank you for your detailed work on this document.*

Reviewer: Robert Vincin

General Comment

Comment*: The point is missed about cause effect solution on climate change. I sat in UNTAD UNFCCC etc assemblies from 1996. I am in PRC lowering* CO_2 *as invited foreign expert since 2005. Volcanoes emitted mass* CO_2e *nitrates sulfate for living matter to breath sequester. Emissions from power stations steel-mills are micro volcanoes. The principal climate change issue is mass land use land use clearing desertifcation and now no working no C4* CO_2 *sinks. I am a foreign expert guest in PRC since 2005 lowering* CO_2 *and in so doing reversing deserts and the mass global cloud, restarting rain cycles. USA Senators are looking in the wrong place. The historians of tomorrow cannot wait until it is their turn 2020-50 as the bees birds micro organism are failing to work. Rain and trace element cycles along with* CO_2 *cycles have stalled. The Senate should come visit work as a global unit. We need new thinking working practicing delegates at COP16 to detail simple low cost solution BAU We borrowed the Planet from the historians let up put it back in working and balanced order.*

Reviewer: Michael Wondsidler

General Comment

Comment*: The US GHG Inventory should integrate a systems-based view and include this along with the normal sector-based view. When viewed together, the traditional sector-based view and the systems-based view offer a broader and easier to understand view of US GHG emissions. Both citizens and government representatives can benefit from a systems-based view and find this approach enlightening and educational in formulating choices and political actions to find solutions to counteract climate change.*

Comment*: Emissions resulting from personal and organizational consumption should be included in the US Greenhouse Gas Inventory. The US Greenhouse Gas Inventory should be state that the inventory is limited to emissions that physically originate within the national borders of the US. It should relate that imports for US consumption creates emissions that are counted in the inventories of other nations. Emissions from US exports are less than those from goods the US imports. Since we must also include the impacts of our consumption, the GHG emissions of the US is higher than suggested by the current IPCC accounting methods. This is really important:*

Consumption is the reasons for the emissions, and not including this will give critics of the EPA justification that the US Inventory is not a realistic picture of how much the US contributes to GHG emissions. Also, this encourages businesses and economic value to leave the US for other countries not counted in our inventory.

Comment*: Since we need to reduce the current and short term impacts of GHGs, we should also include the US inventory results using both the 100-year and 20-year global warming potentials*

(GWPs). This analysis would be helpful to citizens and governmental planners and decision makers.

Reviewer: Peter Schultze, Environmental Programs Analyst, City of Emeryville Public Works Department

General Comment

***Comment**: Products and consumption of products and their domestic and international GHG related emissions need to be formally addressed in the inventory. It is something sorely lacking in most CAPs including the one developed by me for my jurisdiction.*

General Comment

***Comment**: The views of emissions both by sector and systems analysis need to be presented so that more of the whole picture is understood.*

General Comment

***Comment**: Shorter-term GWPs are illustrative of important issues; such as the differences between methane and* CO_2 *emissions, for example, and the relation to organic materials in the landfill. A 20 year GWP analysis would be helpful in creating our local policies and should be considered for the document.*

Reviewer: Chris Cuomo

General Comment

***Comment**: My comment is that the public needs to know more about greenhouse gas emissions and other pollution caused by the military, at home and abroad. I therefore request that that information be included in the final report. The fact that the IPCC does not require reporting is irrelevant to the American public's need to know.*

***Comment**: My question is whether you are able to direct me to any sources for [information about greenhouse gas emissions and other pollution caused by the military, at home and abroad].*

Reviewer: Bailey Payne, Waste Reduction Coordinator, Marion County Public Works

General Comment

***Comment**: I've been working with a group called the West Coast Climate Forum which is made up of people working for the EPA, state & local governments. We have been discussing the importance of integrating a system-based view with the traditional sector-based view when it comes to inventorying where green houses come from. Much of the greenhouse gases associated with materials are released when natural resources are extracted or products are manufactured* *and this isn't well reflected in the traditional sector-based model. Thank you for your consideration.*

Reviewer: Sego Jackson, Principal Planner, Snohomish County Solid Waste Division

General Comment

Comment*: The US Inventory should integrate a systems-based or consumption-based view and present it alongside the sector-based view. Even if a detailed analysis is not available, providing text and graphics that demonstrate how an alternate view provides valuable information for policy and program development would be tremendsouly helpful to the public, stakeholders, policy makers and planners. coupled with the traditional sector-based view, the systems-based view offers a much more comprehensive perspective on how the US contributes to GHG emissions. At the very least this should be included under "planned improvements" in the waste section.* [See Appendix B for additional details.]

Comment*: Consumption-related emissions should be formally acknowledged in the US Greenhouse Gas Inventory. The US Greenhouse Gas Inventory should be much more explicit in stating that the inventory is limited to emissions that physically originate within the national borders of the US. It should explain that the US also contributes to emissions that are counted in the inventories of other nations, as a consequence of imports. The emissions associated with US exports are less that those associated with US imports. When viewed from the perspective of consumption, the greenhouse gas impact of the US is higher than suggested by the traditional IPCC accounting standard. This is of great importances: consumption is the root cause of emissions. Until this is clearly explained and addressed, stakeholders, policy makers, and planners will not understand the key overarching strategy of reducing consumption of energy and resources.* [See Appendix B for additional details.]

Comment*: Please include both 100-year and 20-year global warming potentials (GWPs) in the Inventory. While the Inventory points out that other GWPs are also available it would be more useful to actually include that analysis in the Inventory to assist policymakers, planners, and stakeholders.* [See Appendix B for additional details.]

Reviewer: Ralph J. Villani, Esq.

Energy

Comment*: Why not use methane gases from coal mines as an energy source instead of scubbing it into the atmosphere; maybe that might prevent another coal mine disaster and loss of life.*

Reviewer: Carey Hamilton, Executive Director, Indiana Recycling Coalition

General Comment

Comment*: On behalf of the Indiana Recycling Coalition (IRC), I am writing to encourage the U.S. Environmental Protection Agency to integrate the systems-based view in the U.S. Greenhouse Gas Inventory and present it alongside the traditional sector-based view. EPA recently published a "systems-based view" - see chart, p. 11, of GHG emissions. Coupled with the traditional sector-based view, the systems-based view offers a much more comprehensive perspective on how the US contributes to GHG emissions, in particular in the area of materials management. As a statewide education and advocacy organization the IRC works to advance a more sustainable materials management system, including advocating for stronger waste reduction, reuse, recycling and composting policies, in our state. We find the systems-based view to be very informative and instructional in developing policy actions to advance these efforts while simultaneously addressing climate change. Thank you for the opportunity to comment on this policy-making process. I can be reached at the number below should you have any questions about the IRC's position on this important issue.*

Reviewer: Jennifer Dawani, Environmental Scientist, Air and Waste Management Division of U.S. EPA (Region 7)

General Comment

Comment*: Adding a systems-based viewpoint on our emissions consistent with OSWERs report - http://www.epa.gov/oswer/docs/ghg_land_and_materials_management.pdf> see chart, p. 11, of GHG emissions. to give a more comprehensive perspective on how the US contributes to GHG emissions. Regardless of data limitations, I sincerely urge you to formally acknowledge consumption-related emissions in the inventory. The inventory should be much more explicit in stating that the inventory is limited to emissions that physically originate within the national borders of the US and acknowledge that the US also contributes to emissions attributed to other nations, as a consequence of our imports. This is important because consumption is the root cause of emissions, that we must at least acknowledge.*

Reviewer: Edward A. Mainland, Co-chair of Energy-Climate Committee, Sierra Club California

Landfills

Comment*: Methane Emissions from Landfills. Methane emissions are one of the most dangerous near-term emissions problem in the entire GHG picture. Most widely used methods unfortunately may seriously underestimate the problem of methane emissions from landfills. They particular underestimate the near-term emissions (three years) which are most significant. They also underestimate the greenhouse power of these emissions. They underestimate the percentage of GHG emissions caused by landfills. And they miscalculate how much methane can be recovered and used in Landfill Gas To Energy operations and they overly credit the GHG reduction benefit of these operations. EPA's Inventory is the logical place to immediately rectify these analytic and factual shortcomings and misapprehensions. As a separate filing, you will be receiving a recent paper on this problem by Jim Stewart, Sierra Club's Los Angeles Chapter. The need to reduce short-term impacts of GHGs such as landfill methane is imperative. EPA's inventory should present GHG results using both 100-year and 20-year global warming impacts*

(GWPs). IPCC standards require the use of 100-year Global Warming Potentials (GWPs). EPA's inventory should not only point out that other GWPs are available but should include the other, alternative underlying analyses so that policymakers, state and local government energy staffers, and the public may be aware of them and start taking them more into account in policy and operations.

Comment: *Acknowledge consumption-related emissions. Please ensure that EPA's GHG Inventory is crystal clear in noting that the Inventory is focussed only to those GHG emissions that are produced inside U.S. borders. The Inventory also should make clear that the U.S. also emits carbon that other nation's inventories count. That's because of imports. Carbon emissions from U.S. exports are smaller than those reckoned from imports to this country. That means that consumption-wise, U.S. carbon impacts are considerably higher than conventional IPCC reckoning admits. The EPA Inventory should explain why this is do. It's widely recognized that the chief source of emissions is consumption. EPA presumably would wish to avoid criticism that it's failing to assess and measure all these consumption impacts. EPA needs to convince decision makers, the media and the public that the Inventory really does give a complete and reliable picture of U.S. carbon emissions. EPA doesn't need to engender this kind of criticism unnecessarily. By giving a full look at consumption impacts, EPA can and should avoid causing complaints that EPA is indirectly rewarding off-shoring of emissions and the employment that goes along with that.*

Comment: *Priority to systems-based view over traditional sector-based view. EPA's recently published a "systems-based view" http://www.epa.gov/oswer/docs/ghg_land_and_materials_management.pdf (chart, p. 11, GHG emissions) was welcome and beneficial. A systems-based view clearly presents a more complete and useful approach to assessing how much the United States is responsible for world carbon emissions. EPA should give the systems-based approach more visibility so that local officials and the public at large can work from a sounder basis in formulating actions to address carbon emissions more productively, effectively and scientifically.*

Reviewer: Matt Korot, Resource Conservation & Recycling Program Director, Metro

General Comment

Comment: *Metro, the elected regional government serving nearly 1.5 million citizens in the Portland, Oregon metropolitan area, recently conducted an inventory of greenhouse gases for our region. In developing this inventory, Metro utilized the systems-based approach detailed in EPA's Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices report. As a national leader in developing policies and programs to reduce waste, Metro finds the systems-based approach to be a useful tool for identifying and analyzing additional policies to reduce emissions. It enables us to explicitly show how consumption of goods and food makes a significant contribution to greenhouse gas emissions. I strongly encourage you to include the systems-based inventory methodology alongside the traditional sector-based accounting approach contained in the draft U.S. inventory. Integrating the systems view into the U.S. inventory report would encourage other states and local governments to consider this approach, resulting in a more comprehensive set of policy tools to address emissions.*

***Comment**: In addition, I encourage you to include in your report both the 100-year Global Warming Potential (GWP) and a 20-year GWP. The shorter timeframe provides more consistency with our regional planning efforts and provides a better frame of reference by which to actively engage our citizens.*

Reviewer: Julie Muir, PSSI/Stanford Recycling

General Comment

***Comment**: The US Inventory should integrate the systems-based view and present it alongside the traditional sector-based view. EPA recently published a "systems-based view" < http://www.epa.gov/oswer/docs/ghg_land_and_materials_management.pdf > see chart, p. 11, of GHG emissions. Coupled with the traditional sector-based view, the systems-based view offers a much more comprehensive perspective on how the US contributes to GHG emissions. The sector based view only deals with end of the tailpipe solutions and doesn't put to solutions that will get us to 80% reduction. The general public and local policy makers find the systems-based view to be very informative and instructional in developing personal and policy actions to address climate change.*

***Comment**: Consumption-related emissions should be formally acknowledged in the US Greenhouse Gas Inventory. The US Greenhouse Gas Inventory should be much more explicit in stating that the inventory is limited to emissions that physically originate within the national borders of the US. It should explain that the US also contributes to emissions that are counted in the inventories of other nations, as a consequence of imports. The emissions associated with US exports are less than those associated with US imports. When viewed from the perspective of consumption, the greenhouse gas impact of the US is higher than suggested by the traditional IPCC accounting standard. This is of great importance: consumption is the root cause of emissions, and failure to at least acknowledge the impacts of consumption exposes EPA to unnecessary criticism that the US Inventory is providing an incomplete picture of how the nation contributes to emissions (and indirectly, rewarding off-shoring of emissions and associated jobs).*

***Comment**: Given the need to reduce the short-term impacts of greenhouse gases, it would be very helpful if the US Inventory portrayed results using both 100-year, and 20-year GWPs. While the IPCC standards require the use of 100-year Global Warming Potentials (GWPs), the Inventory correctly points out that other GWPs are also available, and including that analysis would be helpful to planners, policymakers, and the public.*

***Comment**: The information in the EPA report on Products and Packaging should be included.*

Waste

***Comment**: The bizarre treatment of landfills and incinerators as well as biogenic emissions makes it difficult to advocate for the proper solutions to material management, leading to more wasting of materials. It also undermines work in this field at the state-level.*

Reviewer: Laurence K. Lau, Deputy Director for Environmental Health, State of Hawaii

Waste

Comment*: While the draft seems very comprehensive, I ask that it or future versions include an analysis of materials management. For example, the EPA OSWER presented in Hawaii another look at emissions that provided a useful perspective. Closing the Loop on Climate Change, Edward Chu, October 23, 2008 (Center for Program Analysis, OSWER, chu.ed@epa.gov) It highlights the roles of buildings, land use patterns, and providing goods, items that are indirectly covered by the draft inventory. The materials management approach is easier for some people to grasp, and policy makers benefit from having a variety of tools.*

General Comment

Comment*: I also ask for some analysis of life cycle issues. Life cycle analyses may be necessary to describe materials management properly, as "things" often represent imbedded energy and emission costs.*

Reviewer: Rick Albright, Director, Office of Air, Waste & Toxics, U.S. EPA Region 10

General Comment

Comment*: The Executive Summary of the 2010 Draft U.S. Greenhouse Gas (GHG) Inventory provides a discussion of an alternative view of GHG emissions with the inclusion of "emissions by economic sector." We recommend that this be expanded to also include a presentation of emissions by economic system, based on the systems approach to the U.S. GHG Inventory included in OSWER's 2009 report, Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices.*

Assisting government, business and public understanding of the complex connections between the economy, consumption and GHG emissions is one of EPA's essential roles. OSWER's 2009 report provides important new thinking on GHG emissions by re-casting the U.S. GHG Inventory into a system-based view of the data. By presenting a life cycle perspective of GHG emissions associated with providing goods and food to the economy, the systems-based view demonstrates important opportunities to reduce GHG emissions through the management of materials from resource extraction through end-of-life. The systems-based inventory also illustrates the important connections between land management decisions and GHG emissions, especially emissions from transportation. As discussed in the OSWER report, this perspective daylights important prevention-oriented mitigation strategies that can enhance the overall effectiveness of our climate protection program. Several large cities on the West Coast are already beginning to incorporate this thinking into their climate actions plans.

Reviewer: Shannon Binns, Program Manager, Green Press Initiative

General Comment

Comment: *As a member of the Land Use Technical Working Group (TWG) for the new GHG Protocol Product Life Cycle Accounting and Reporting Standard, I can also tell you there is a strong interest from organizations who are measuring and trying to reduce their GHG impacts to have guidance in this area as well, and that has been our working group's task. We have recognized that despite the complexity of measuring product carbon footprints for products that rely heavily on the harvesting of natural resources -- such as paper products -- it is necessary to provide some guidance for measuring these impacts and have done so in the new draft standard. The draft standard has already been tested by 60 companies and as you can read in this article, "Increasingly, companies are looking beyond their own boundaries and developing strategies to reduce GHG emissions in their supply chains and in the products they make and sell," [said] Bjorn Stigson, president of WBCSD. "By taking a comprehensive approach to GHG measurement and management, businesses and policymakers can focus attention on the greatest opportunities to reduce emissions within the full value chain, leading to more sustainable decisions about the products companies buy, sell, and produce."*

Reviewer: John Davies, Sustainable Transport and Climate Change Team, Office of Natural and Human Environment, Federal Highway Administration

Mobile Combustion

Comment: *The impact of rising biofuel utilization on transportation CO_2 trends should be clarified in EPA's inventory. DOT recognizes that biofuel combustion CO_2 is not included in energy sector totals, since it's assumed that CO_2 released during combustion is re-absorbed as biofuel crops regenerate. However, the inventory's combustion-only estimates are often used as the basis for calculating upstream emissions, which can be considerable for biofuels. This suggests the need for an expanded discussion of GHG accounting issues in the context of transportation GHG trends, as well as the inclusion of placeholder data to allow for the fuel cycle calculation.*

Comment: *Transportation estimates in Tables such as 2-15 and 3-12 could include tailpipe biofuel combustion estimates as an italicized item similar to the "wood biomass and ethanol consumption" estimate currently presented in Tables ES-2 and 3-1. It would also be worthwhile to include a footnote explaining why these emissions are not included in the total.*

Comment: *It could also be very helpful to include actual transportation biofuel consumption data in the Annex. This information could be included as an italicized subitem (beneath the main table) in Annex 2 Tables A-10 to A-29, or in the front section of Annex section 3.2.*

Comment: *The impact of increased biofuel consumption (and the related accounting issues) could also be discussed in the transportation narratives of Sections 2.1 and 3.1, which could also point to the RFS literature for details on upstream analysis of transportation fuels.*

Reviewer: Joe Carriero, National Park Service

General Comment

***Comment**: Under the Executive Order "Federal Leadership in Environmental, Energy, and Economic Performance" issued in October 2009, federal agencies are now required to "measure, report, and reduce their greenhouse gas (GHG) emissions from direct and indirect activities." The Department of Energy (DOE) Federal Energy Management Program (FEMP) in cooperation with other federal agencies has developed the Federal Greenhouse Gas Accounting and Reporting Guidance to define methods for reporting emissions. EPA should ensure that methods used in this annual inventory of greenhouse gas emissions and sinks are consistent with the FEMP methodologies. If source categories or reporting methods differ, it would be appropriate to define the basis for differences in a new section added to this report.* [See Appendix C for additional details.]

Land Use, Land Use Change, and Forestry

***Comment**: The inventory results are informative and for the most part clearly presented. While we agree that currently available methods make it difficult to specifically quantify the impacts of forest fires on net carbon sequestration in forests, EPA should acknowledge the numerous efforts by federal agencies to improve methods to characterize fire emissions. Future inventories may be able to refine these estimates.* [See Appendix C for additional details.]

Reviewer: S. Rao Chitikela, Ph.D, P.E., BCEE

Wastewater

***Comment**: Are the* CO_2 *emissions of wastewater treatment using aerobic/anaerobic bio-processes considered in this report?*

-- CO_2 *emissions of biological activated sludge processes and other nitrification/denitrification processes are significant.*

***Comment**: Are the* CO_2 *emissions of fuel combustion operations at the POTWs considered for this report?*

-- For example, fuel-oil or natural gas (or recovered biogas or other fuel) is fired in the sludge heaters to maintain the mesophilic temperatures of the anaerobic sludge digesters.

Reviewer: Tom Huetteman, Associate Director, Waste Management Division, U.S. EPA Region 9

General Comment

***Comment**: The Executive Summary of the 2010 Draft U.S. Greenhouse Gas (GHG) Inventory provides a discussion of an alternative view of GHG emissions with the inclusion of "emissions by economic sector." We recommend that this be expanded to also include a presentation of emissions by economic system, based on the systems approach to the U.S. GHG Inventory included in OSWER's 2009 report, Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices. Assisting government, business and public understanding of the complex connections between the economy, consumption and GHG emissions is one of EPA's essential roles. OSWER's 2009 report provides important new thinking on GHG emissions by re-casting the U.S. GHG Inventory into a system-based view of* *the data. By presenting a life cycle perspective of GHG emissions associated with providing goods and food to the economy, the systems-based view demonstrates important opportunities to reduce GHG emissions through the management of materials from resource extraction through end-of-life. The systems-based inventory also illustrates the important connections between land management decisions and GHG emissions, especially emissions from transportation. As discussed in the OSWER report, this perspective daylights important prevention-oriented mitigation strategies that can enhance the overall effectiveness of our climate protection program. Several large cities on the West Coast are already beginning to incorporate this thinking into their climate actions plans. We recognize the need for careful deliberation when making changes to the Inventory, and we would like to begin a robust internal dialogue on this recommendation. Please feel free to contact me to discuss further our recommendation.*

Reviewer: Paula Wise, Deconstruction & ReUse Network

Waste

***Comment**: This is a incredibly important act. I hope that you will to incorporate Reuse and deconstruction into the mix. I understand Recycling is included. Recycling is good, but reuse is better. Keeping items in there original state reduces greenhouse gases. I ask that you please consider this.*

Reviewer: Joyce Dillard

Energy, Oil & Gas

***Comment**: Since oil wells are on residential property in the City of Los Angeles, how are emissions gauged separately in relationship to automobiles or other industry emissions? Is there a danger that these emissions can be masked under an industrial veil and not production?*

***Comment**: How is fracking being addressed for oil extraction?*

***Comment**: How is subsidence being handled in relationship to gas leakage?*

General Comment

***Comment**: Is there a groundwater quality standard for landfills and/or oil fields.*

***Comment**: Are there requirements to report and measure any de-watering as a Methane Mitigation?*

***Comment**: Methane Mitigation Standards do not seem to exist. Are there Federal standards? If so, do they address NPDES requirements?*

Reviewer: Kyle Meisterling

Annex 3

***Comment**: Annex 3, "Methodology for Estimating CH_4 emissions from Landfills" (p A-280), The heading # reads "3.1." should probably be 3.14.*

Reviewer: Karin Ritter, American Petroleum Institute

Energy, Petroleum Systems

***Comment**: API recently revised the API Compendium. References to emission factors from the API Compendium should be updated to reflect the 2009 version of API's Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry. For example, Section 3.7 Petroleum Systems (p. 3-49, line 22 and p. 3-50, line 27) and Annex 3.5 Petroleum Systems (p. A-149, line 32) reference "API (2004)". Note: the emission factors referenced in these citations did not change between the 2004 and 2009 editions.*

***Comment**: The most significant change noted in the 2008 national inventory was the addition of asphalt blowing CO_2 emissions for refineries in the Petroleum Systems category. This emission source accounts for 36% of the total non-combustion CO_2 emissions from petroleum systems in 2008. The CH_4 factor for asphalt blowing is the same as is used in the 2007 EPA Inventory of Greenhouse Gas Emissions and Sinks. However, neither emission factor is consistent with the 2009 API Compendium.*

The 2009 API Compendium cites a simple emission factor for uncontrolled asphalt blowing from AP-42 (EPA, AP-42, Section 5.1.2.10, 1995). The AP-42 emission factor for asphalt blowing is assumed to be on an air-free basis (AP-42 does not specify this, but notes the factor represents "emissions"). Asphalt blowing exhaust composition data (13 mol% CH_4 and 9 mol% CO_2, on an air free basis) presented in an Oil & Gas Journal article is applied to derive the CH_4 and CO_2 emission factors of 5.55E-4 tonnes CH_4/bbl asphalt blown and 1.01E-3 tonnes CO_2/bbl asphalt blown, respectively. (Further details on the derivation of these emission factors is provided in Appendix B of the 2009 API Compendium.)

For comparison, the EPA emission factors converted to a similar basis are 4.9E-5 tonnes CH_4/bbl and 1.09E-3 tonnes CO_2/bbl. However, the primary distinction between the API Compendium emission factors and those used in the EPA inventory is the units of measure applied to the activity factor. The API emission factors are based on the volume (or mass) of asphalt blown, while the EPA emission factors appear to be based on the total volume of asphalt produced (411 Mbbl/cd production). As a result, the EPA emission factors result in much higher emission estimates.

Energy, Natural Gas & Petroleum Systems

***Comment**: EPA notes under planned improvements for both the Natural Gas Systems and Petroleum Systems source categories that results from two studies on flashing losses from oil and condensate tanks will be reviewed for the next inventory update cycle. API and its member companies provided comments last August on the study by the Texas Commission on Environmental Quality. API expressed serious concerns over the presentation of results from that study, where differences between model-estimated values and field data were reported as errors in the model calculations, and in the lack of information provided to evaluate measurement data quality. API is concerned that this report inadequately portrays the reliability of emissions estimation methods commonly used in the oil and natural gas industry, and may result in erroneous conclusions about the credibility of widely used flash emission models. In addition, the extrapolation of the report findings to estimating methane emissions from work specifically addressing Volatile Organic Compounds emissions is inappropriate.*

***Comment**: There are a number of sources that do not appear to be included in the national GHG inventory. For the refining sector, these include CO_2 emissions from flares, catalytic cracking units, fluid coking units, catalytic reforming units, sulfur recovery units, and coke calcining units. Emissions from each of these sources are required to be reported under the Mandatory GHG Reporting Regulation (MRR), and for which EPA had to assess the emissions as part of the justification for their inclusion in the MRR. The inventory should incorporate EPA's current understanding of these emissions or document why they are excluded from the inventory.*

Annex 3.4, Natural Gas Systems

***Comment**: Emission factors and activity factors are only provided for 2008 (with the exception of "key activity data drivers" provided in Table A-114), yet emissions are shown for multiple years. Recommend adding emission and activity factors for all years for which emissions are being estimated, for full disclosure. (In addition, it is discussed in Step 1 that activity factors vary by year.)*

***Comment**: If emission factors determined for 1995 are assumed to be representative of emissions from each source type over the period 1990 through 2008, recommend adding that information to Step 1 or Step 3, similar to the text in Annex 3.5 Petroleum Systems, p. A-149, line 19.*

***Comment**: Table A-112 - Recommend showing non-zero values for emission factors for the following activity types: Turbines (Storage), Generators (Engines), and Generators (Turbines). Emissions from these sources are not zero; therefore the emission factor must also not be zero.*

***Comment**: Table A-114 - Activity counts for "Non-associated Gas Wells" correspond to the sum of the count of "Non-associated Gas Wells" and "Unconventional Gas Wells" presented in Table A-110 and A-117. Recommend adding a footnote to Table A-114 to reflect this summation.*

***Comment**: Emissions for the year 2000 are missing from all tables in this annex; however, they are shown in Section 3.6 (Tables 3-37 through 3-40). Emissions (and all data used to derive emissions) for the year 2000 should be added to Annex 3.4.*

***Comment**: Activity factors are only provided for 2008, yet emissions are shown for multiple years. Recommend adding activity factors for all years for which emissions are being estimated, for full disclosure. (In addition, it is discussed in Step 2 that activity factors vary by year.) Text should also be added to Annex 3.5 defining the sources of the activity factor data.*

Reviewer: Kevin Bundy, Senior Attorney, Center for Biological Diversity

Biomass Burning

***Comment**: EPA's inventory document repeats a pernicious assumption that has profound consequences for both the climate and the nation's forests: the assumption that biomass combustion is "carbon neutral." EPA recognizes, as it must, that the combustion of biomass and biofuels produces CO_2 and other greenhouse gases. Yet EPA declines to include these emissions in national totals "because biomass fuels are of biogenic origin." According to EPA, "[i]t is assumed that the carbon (C) released during the consumption of biomass is recycled as U.S. forests and crops regenerate, causing no net addition of CO_2 to the atmosphere." As described in detail below, scientists have concluded that this assumption represents a critical error in*

EPA's climate accounting methodology. This error pervades all of EPA's biomass calculations, but it is especially glaring as applied to facilities that burn woody biomass from tree plantations, forest thinning projects, or fire salvage projects. Promotion of new and expanded biomass energy facilities predicated on this assumption is beginning to threaten both the ecology of the nation's forests and the stability of the world's climate. EPA thus should revise the Inventory to eliminate reliance on the "carbon neutrality" assumption and should adopt accounting methods that accurately measure emissions from both biomass combustion and associated land use change on time scales relevant to climate protection efforts. [See Appendix D for additional details.]

Reviewer: Bill Sheehan, Product Policy Institute (plus 62 other organizations' signatures)

General Comment

***Comment**: The US Inventory should integrate "systems-based" greenhouse accounting -- and present it alongside the traditional sector-based view.*

***Comment**: Consumption-related emissions should be formally acknowledged in the US Greenhouse Gas Inventory. The US Greenhouse Gas Inventory should be much more explicit in stating that the inventory is limited to emissions that physically originate within the national borders of the US. It should explain that the US also contributes to emissions that are counted in the inventories of other nations, as a consequence of imports.*

***Comment**: Given the need to reduce the short-term impacts of greenhouse gases, the US Inventory should portray results using both 100-year, and 20-year Global Warming Potentials. While the IPCC standards require the use of 100-year Global Warming Potentials (GWPs), the Inventory correctly points out that other GWPs are also available, and including that analysis would be helpful to planners, policymakers, and the public.*

Reviewer: Cynthia A. Finley, Ph.D, Director, National Association of Clean Water Agencies

Water – Wastewater Treatment

***Comment**: NACWA believes that using the literature nitrogen loading values or EPA-collected values from U.S. POTWs would better reflect the actual emissions from POTWs in the U.S. than the current methods based on the IPCC Guidelines. The IPCC Guidelines do not necessarily reflect actual conditions at POTWs throughout the U.S. This is illustrated by the emission factor ("EF1") of 3.2 g N_2O/person-year for plants with no intentional denitrification, used in the Draft Inventory and in the IPCC Guidelines to calculate nitrous oxide emissions from centralized wastewater treatment plants. This value was obtained from a single study of a very small wastewater treatment plant (1.06 million gallons per day, or MGD) in a small university town in New Hampshire. The population of this town is 12,500 during the school year, but drops to 6,200 in the summer months, during which most of the measurements for this study were made. If the IPCC can use this single study to define an emission factor that is used for centralized treatment facilities all over the world, certainly EPA can justify changing the nitrogen loading* *rate for facilities in the U.S. based on multiple literature values and data that it can collect from POTWs across the nation.* [See Appendix E for complete comment.]

***Comment**: In the $N_2O_{WOUT\ NIT/DENIT}$ equation (line 44, page 8-13), the FIND-COM factor should be moved outside of the square brackets. This is a typographical error rather than an error that affects the calculations.*

***Comment**: In the $N_2O_{EFFLUENT}$ equation (line 45, page 8-13), the USPOP factor should be multiplied by the WWTP factor, as it is in the $N_2O_{WOUT\ NIT/DENIT}$ equation, since septic system users should not be included in the amount of effluent discharged to aquatic environments. NACWA recommends that any nitrous oxide contributions from septic systems be calculated in a separate equation if they are even included in the Inventory.*

***Comment**: The units provided in the definitions of N_2O_{TOTAL}, N_2O_{PLANT}, $N_2O_{NIT/DENIT}$, and $N_2O_{WOUT\ NIT/DENIT}$ (lines 2-7, page 8-14) should be Gg, not kg, since conversions are made to Gg in the equations used to calculate these values.*

***Comment**: The value of 269 Tg N for N_{SLUDGE} (line 37, page 8-14) appears to be an error, resulting in a negative value for $N_2O_{EFFLUENT}$. The value of 141 Gg N found in the Annex in Table A-193 (page A-231) is a more appropriate magnitude. However, even substituting this 141 Gg N value for N_{SLUDGE} does not result in a $N_{TOTA}L$ value that agrees with the value of 15.9 Gg N_2O in Table 8-7. EPA should review the equation for $N_2O_{EFFLUENT}$ and all of the values used in it for accuracy.*

Reviewer: John Davis

Landfills

***Comment**: Landfills emit methane. The Inventory should acknowledge that methane is standardized to CO_2's 100-year atmospheric life, therefore understating methane's real 20-year impact. Please see the attached article "Lifetime Leveraging: An Approach to Achieving International Agreement and Effective Climate Protection Using Mitigation of Short-Lived Greenhouse Gases".* [See Appendix F for article.]

***Comment**: Landfills are credited with carbon sequestration, thereby perversely reducing their methane impact. Common sense dictates that burying anthropogenic carbon should not be considered a GHG reduction. Sequestration credit is particularly perverse in rewarding activities that reduce recycling and composting, where real GHG reduction occurs. Methane avoidance, through recycling and composting, should be acknowledged in the Inventory and full methane production, independent of sequestration, should be presented.*

Waste

***Comment**: Recycling avoids primary extraction and processing, with its associated GHG emissions. Composting reduces GHG emissions from synthetic fertilizer and pesticide production. Food and landscape materials composting avoids methane generation. The Inventory should demonstrate the potential for full recycling and composting benefits, including landfill methane avoidance.*

General Comment

Comment: *EPA's seminal work on materials consumption needs to be incorporated in the Inventory. The 2009 report "Opportunities to Reduce Greenhouse Gas Emissions Through Materials and Land Management Practices" demonstrates the impact of global consumption patterns and systems views, rather than narrowly focused sector based impacts. The Inventory should acknowledge the system and consumption work that will lead to significant policy development.*

Reviewer: Peter Anderson, Executive Director, Center for a Competitive Waste Industry

Landfills

Comment: *Global warming potential. Include in the table showing each sector's responsibility for anthropogenic greenhouse gas emissions the applicable value when current instead of obsolete Global Warming Potential multipliers are used.* [See Appendix G for additional details.] .

Comment: *Short-term strategies. Employ a two-pronged strategy that includes a short-term along with the long-term approach in reported inventory values.* [See Appendix G for additional details.] .

Comment: *First Order Decay Model. Replace the First Order Decay Model, which fails to account for internal moisture levels critical for gas generation, with a revised model that does.* [See Appendix G for additional details.] .

Reviewer: Garrett Fitzgerald, Sustainability Coordinator, City of Oakland

General Comment

Comment: *Include a "systems" or "consumption"-based perspective on GHG emissions within the Draft Inventory.* [See Appendix H for additional details.]

Reviewer: MaryEllen Etienne, Executive Director, Reuse Alliance

General Comment

Comment: *Mention reuse wherever materials management and/or recycling is mentioned in order to acknowledge its significance within the EPA waste management hierarchy and in the handling of GHGs (it is not currently found in the current documentation).*

Comment: *Consider the energy savings and emission reductions of reuse.*

Comment: *Take account of the full life-cycle of materials, from research, extraction, transportation retail, use, and disposal.*

Comment: *Creates a systems-based analysis of direct and indirect emissions or of energy consumption related to materials management.*

Reviewer: Barbara Warren, Executive Director, Citizens' Environmental Coalition

Waste

***Comment**: Seek global agreement to update the methodology so that it reflects the best current scientific information.*

General Comment

***Comment**: Continue to use the agreed upon 2^{nd} IPCC assessment guidance, but add a supplement to the inventory that reflects current understanding of better scientific information. This also will help identify additional opportunities for greenhouse gas reductions. For example, see our discussion of issues related to WASTE below. [Issues discussed are: failure to include upstream GHGs and embodied energy in solid waste, mis-using the SAR 100 year GWP for Methane (should be 20 year), over-estimating LF gas collection efficiency, incorrect treatment of biogenic emissions.]* [See Appendix I for additional details.]

***Comment**: Identify solutions and best practices which can be implemented immediately by state and local governments. All solutions and best practices should be sustainable, offering benefits in 3 spheres -economic, environmental and social-- with no damaging or detrimental drawbacks. Adopting sustainable solutions becomes easy, when multiple benefits, beyond GHG reductions, are within reach.*

***Comment**: Do more analysis at the micro-level. What is the most efficient way to get food from the farm to household dinner tables? the most efficient way to deliver health care? How energy efficient can supermarkets be made? Hospitals? Sewage treatment plants? Schools? Various industries? Etc.*

***Comment**: Strive to make all of the systems we use and rely on - sustainable. Until we do we will not be able to address climate change.*

***Comment**: Immediately address WASTE and WASTING in a much more substantial way. Post World War II we have dramatically increased the amount of waste we generate. WASTE and WASTING are similar to energy losses, except that waste involves the loss or destruction of material resources as well as embedded energy.*

Reviewer: Margaret M. Guerriero, Director, Land and Chemicals Division – EPA Region 5

General Comment

***Comment**: We encourage you to revise the draft inventory to include, at a minimum, a reference to this important and insightful EPA, peer-reviewed resource. Ideally, future versions of the inventory will include both a sector-based and a systems-based view to present a more comprehensive picture of U.S. GHG emissions.* [See Appendix J for additional details.]

Appendix A

UNITED STATES AND GLOBAL DATA INTEGRITY ISSUES

By Joseph D'Aleo
Update October 8, 2009

ABSTRACT

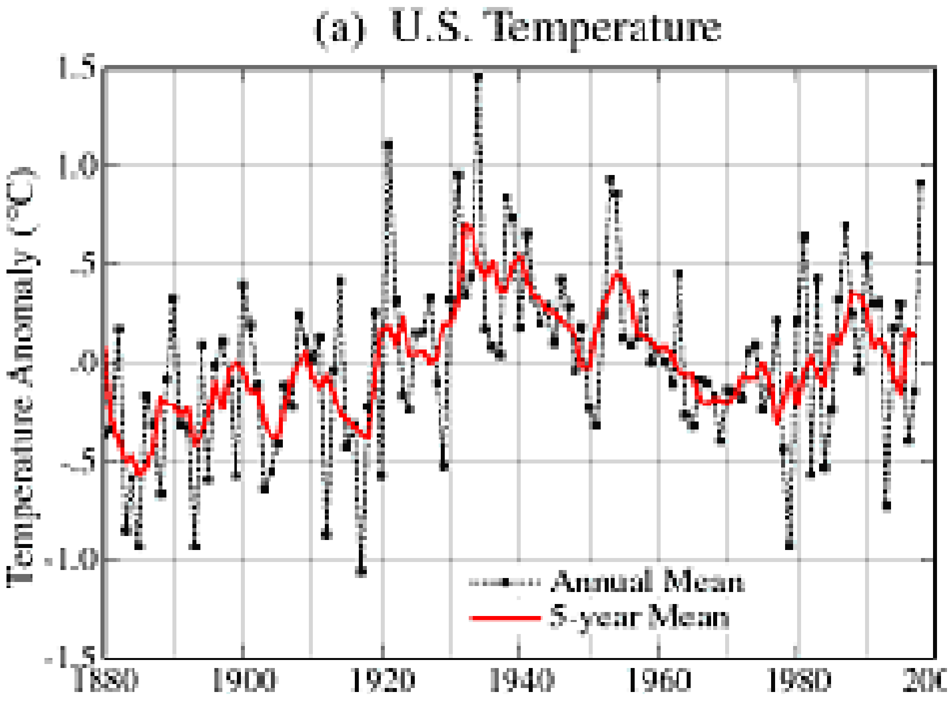
Issues with the United States and especially the global data bases make them inadequate to use for trend analysis and thus any important policy decisions based on climate change. These issues include inadequate adjustments for urban data, bad instrument siting, use of instruments with proven biases that are not adjusted for, major global station dropout, an increase in missing monthly data and questionable adjustment practices.

We hear official press releases announcing 2008 was the 8th, 9th or tenth warmest in 127 to 147 years in the various global data bases. Yet the NASA satellite record shows the year for the globe was the coldest this decade and 14th coldest in the 30 years of satellite monitoring. Here we will show how these global estimates are contaminated and can't be trusted and certainly should not be used for important policy decisions.

US CLIMATE DATA

NOAA NCDC USHCN

When first implemented in 1990 as USHCN version1, it employed 1221 stations across the United States. In 1999, NASA's James Hansen published this graph of USHCN version 1 annual mean temperatures:



About which Hansen correctly noted: ***"The U.S. has warmed during the past century, but the warming hardly exceeds year-to-year variability. Indeed, in the U.S. the warmest decade was the 1930s and the warmest year was 1934."***

USHCN was generally accepted as the world's best data base of temperatures with the stations most continuous and stable, and adjustments made for time of observation, urbanization, known land use changes around sites, and instrumentation changes, each of which can produce major contamination issues for temperature data.

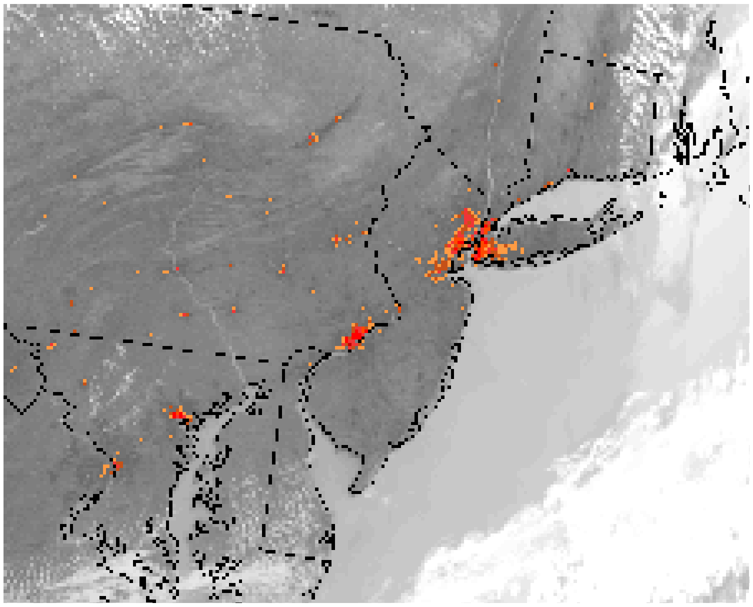
URBAN HEAT ISLAND

There is no real dispute that weather data from cities, as collected by meteorological stations, is contaminated by urban heat island (UHI) bias, and that this has to be removed to identify climatic changes or trends. In cities, vertical walls, steel and concrete absorb the sun's heat and are slow to cool at night. More and more of the world is urbanized (population increased from 1.5 B to 6 B in 1900s).

The UHI effect occurs not only for big cities but also for towns. Oke (who won the 2008 American Meteorological Society's Helmut Landsberg award for his pioneer work on urbanization) had a formula for the warming that is tied to population. Oke (1973) found that the UHI (in °C) increases according to the formula

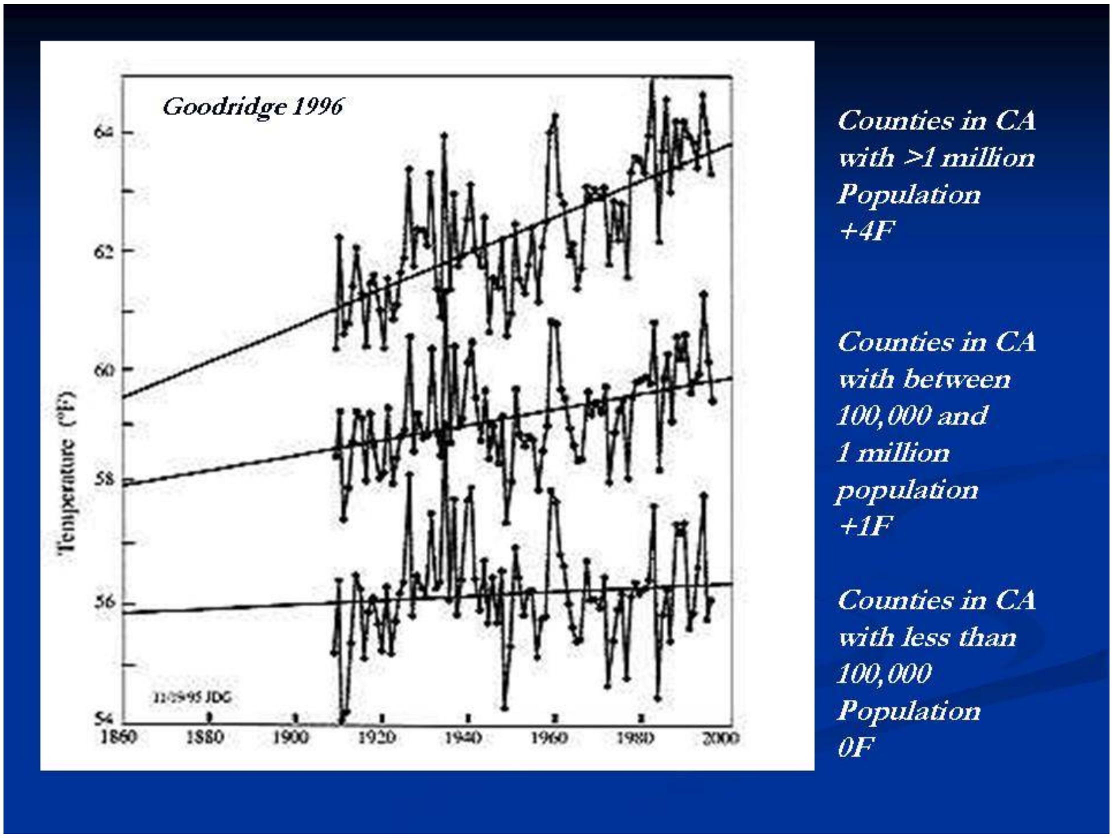
$$UHI = 0.73 \log_{10} \mathrm{POP}$$

where *pop* denotes population. This means that a village with a population of 10 has a warm bias of 0.73°C, a village with 100 has a warm bias of 1.46°C, a town with a population of 1000 people has a warm bias of 2.2C°, and a large city with a million people has a warm bias of 4.4°C.



Urban heat islands as seen from infrared sensors onboard satellites.

Goodrich (1996) showed the importance of urbanization to temperatures in his study of California counties in 1996. He found for countires with a million or more population the warming from 1910 to 1995 was 4F, for counties with 100,000 to 1 million, 1F and for counties with less than 100,000, no change (0.1F).



Counties in CA with >1 million Population +4F

Counties in CA with between 100,000 and 1 million population +1F

Counties in CA with less than 100,000 Population 0F

NCDC’s Tom Karl (1988) employed a similar scheme for the first USHCN data base (released in 1990) that was the best data set available at that time. He noted that the national climate network formerly consisted of predominantly rural or small towns with populations below 25,000 (as of 1980 census) and yet that a UHI effect was clearly evident.

Tom Karl et al’s adjustments were smaller than Oke had found (0.22°C annually on a town of 10,000 and 1.81°C on a city of 1 million and 3.73°C for a city of 5 million).

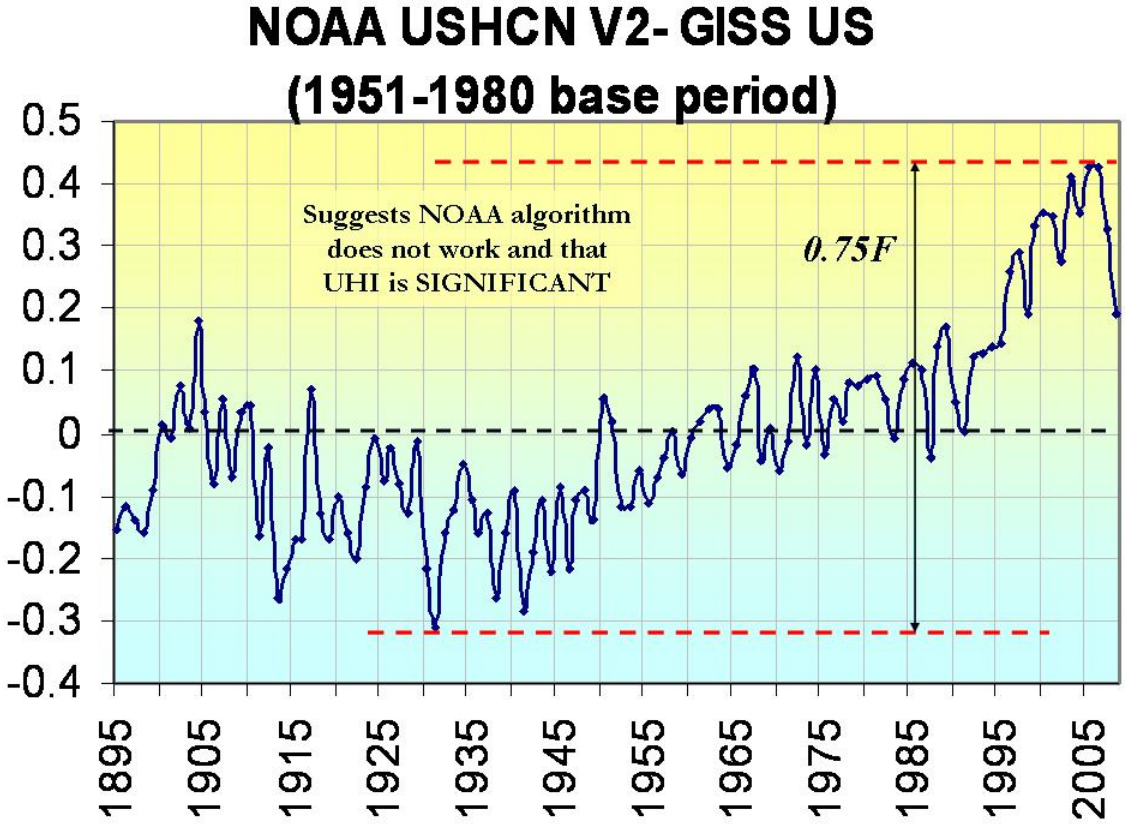
Karl observed that in smaller towns and rural areas the net UHI contamination was relatively small but that significant anomalies showed up in rapidly growing population centers.

USHCN also maintained a METADATA base (not perfect) that identified changes in observing site locations and instrumentation and supposedly made adjustments accordingly, along with adjustment for change in the time of observation over the years.

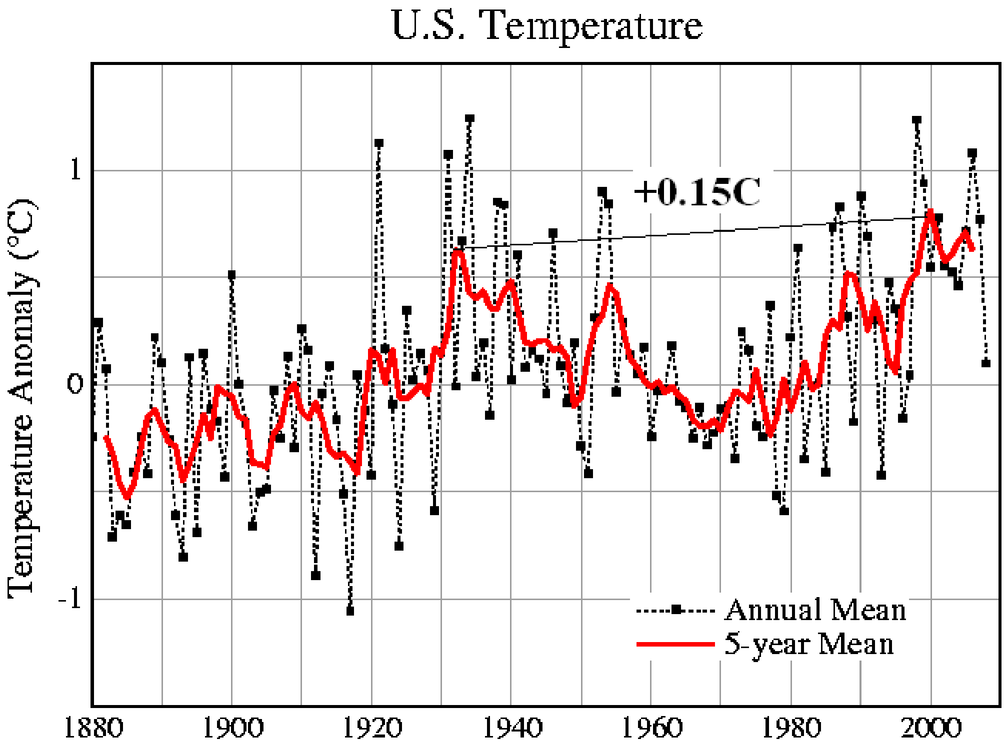
NASA GISS US

GISS uses in the USA, southern Canada and northern Mexico an urbanization adjustment based on the amount of night time light measured by satellites from the station locations. Unlit stations are classified as rural stations. This does produce some adjustment and a reasonable plot of temperatures but as GISS notes, this is just less than 2% of the globe.”

The difference from their adjusted values and the NOAA no longer adjusted shows NOAA was misguided in their removal of the urban adjustment, with a net cooling of 0.2F in 1930s and warming of 0.4F near 2005. NOAA data adjusted to the GISS base period of 1951-1980.



The net warming in the UHI adjusted GISS US data set from the peak around 1930 to the peak near 2000 was a meager 0.15C. It may be assumed the same would be true for the world if we could make a similar needed UHI adjustment.



GISS Adjusted US Temperatures

INSTRUMENT CHANGES

Dr. Ben Herman at the University of Arizona confirmed in working with the climate station in Tucson, AZ that the new HO83 had a significant warm bias. This observation was based on the work by Gall et al. (1992) and Jones (1995). Stephen McIntyre has summarized in The HO-83 Hygro-thermometer (http://www.climateaudit.org/?p=1954) the findings by Tom Karl at al in 1995 of a discontinuity of about 0.5ºC before and after switchover. This change to the HO-83 seemingly went unadjusted for in the USHCN data base for the period from the 1980s to the late 1990s when the instruments were replaced.

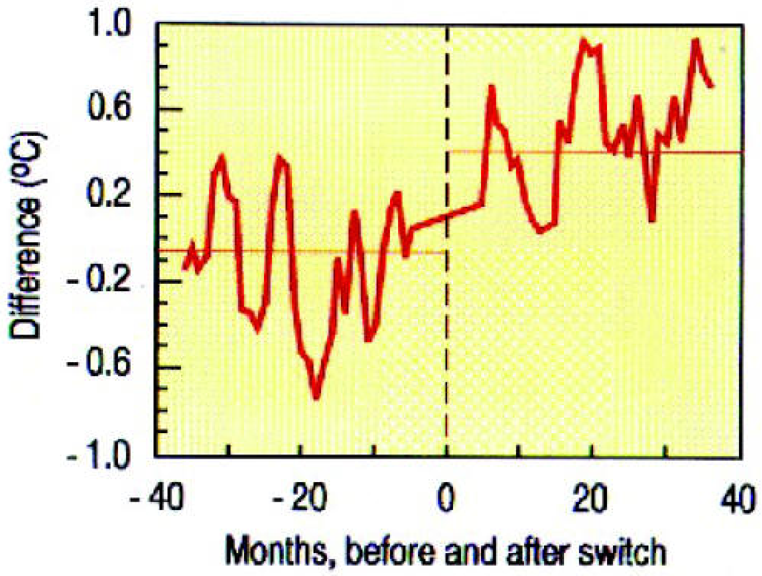


FIG. 2. Effects of changing instruments from the HO63 to the HO83 series on the maximum temperature in the United States (Karl et al. 1995).

BAD SITING

Pielke and Davey (2005) found a majority of stations including climate stations in eastern Colorado did not meet WMO requirements for proper siting. He has extensively documented poor siting and land use change issues in numerous peer review papers, many summarized in the landmark paper Unresolved issues with the assessment of multi-decadal global land surface temperature trends (2007).

Anthony Watts started a volunteer effort to document siting issues with all 1221 stations in US. He and his team is now through over 919 stations. See the results on http://surfacestations.org and numerous examples highlighted on http://wattsupwiththat.wordpress.com. All of these siting issues identified introduce a warm bias.

Here are some examples:

USHCN Station Hopkinsville, KY (Pielke et al 2006)

Max/Min sensor near John Martin Reservoir, CO (Davey 2005)

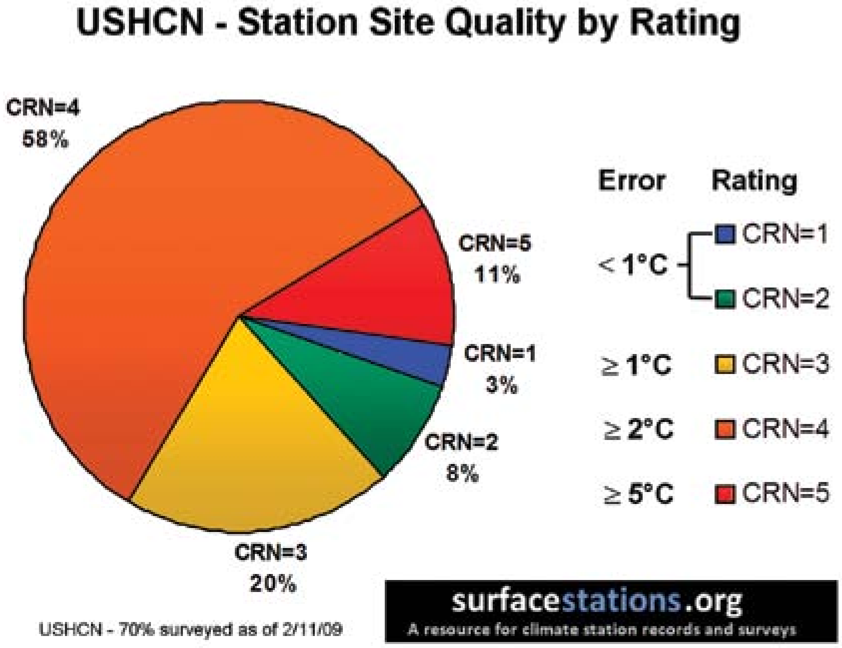
Tucson , Arizona in a parking lot on pavement.

Wickenburg, Arizona next to a building on a paved surface

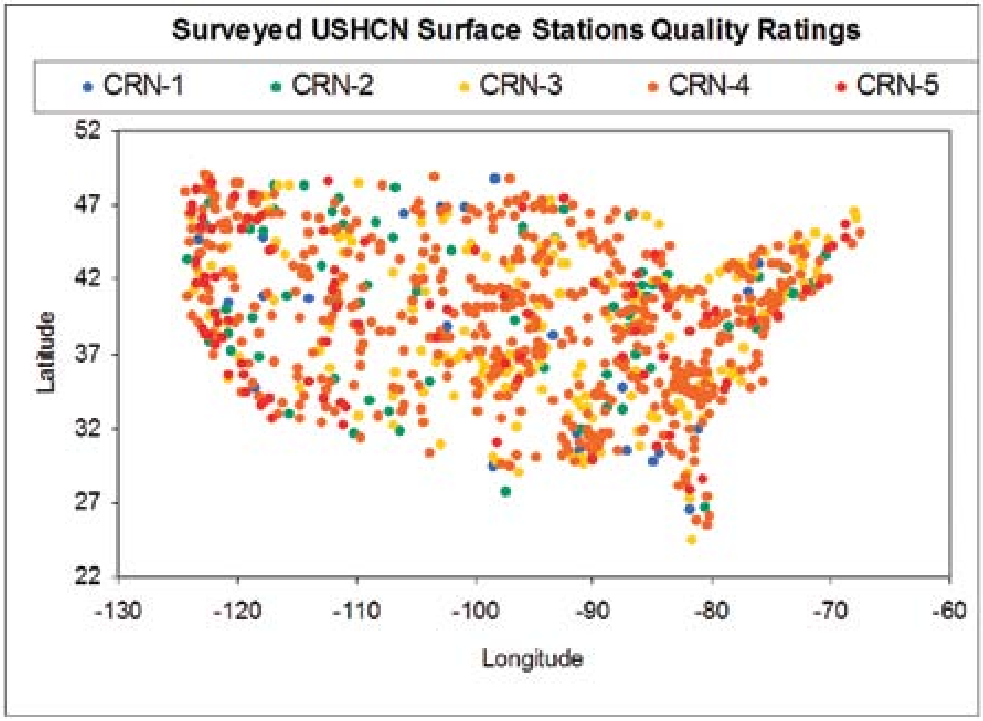
Waterville, WA over volcanic cinders

The vast majority of stations did not meet the governments own criteria for siting as established in the documentation for the Climate Reference Network.

Using the government's own rating system, Anthony has shown a majority of the stations are inadequately sited (89% are CRN 3-5, 69% CRN 4-5 poor to very poor)



The distribution of poor and very poor (CRN 4, CRN 5) was widespread across all the states.



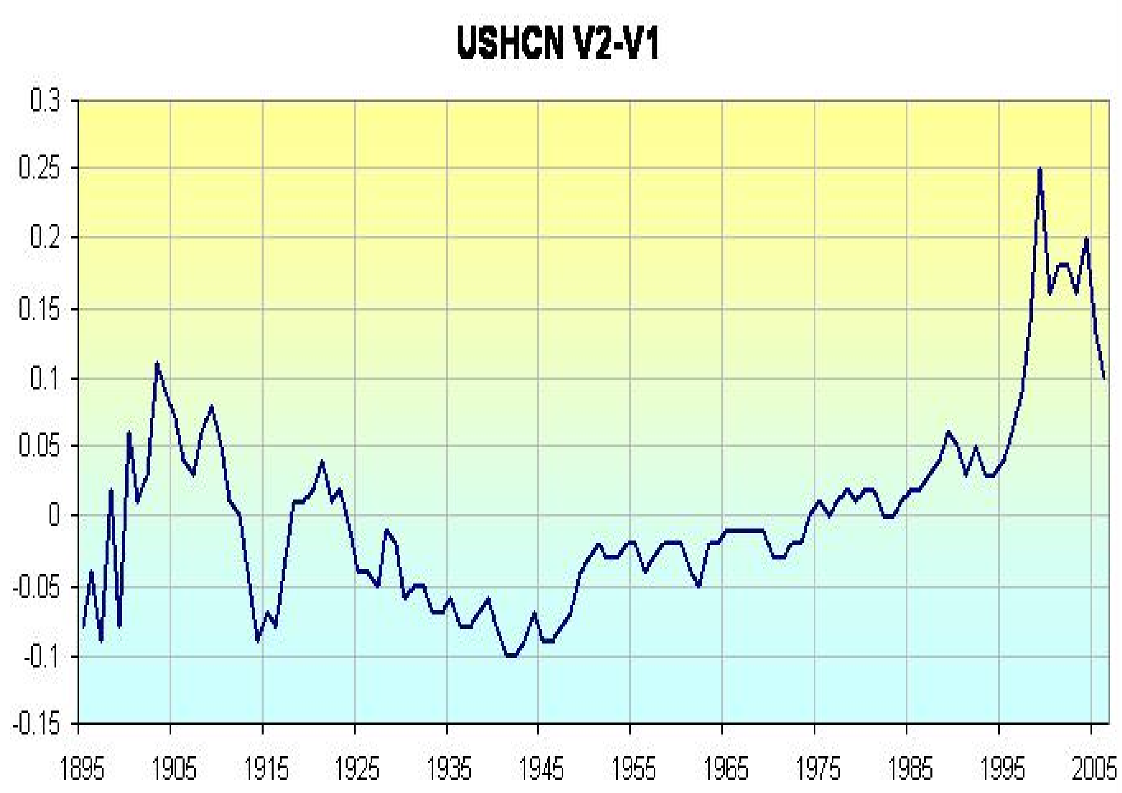
MAJOR CHANGES TO USHCN IN 2007

In 2007 the NCDC (the National Climatic Data Center), in its version 2 of USHCN, inexplicably removed the Karl UHI adjustment and substituted a CHANGE POINT ALGORITHM that looks for sudden shifts (discontinuities). This is best suited for finding site moves or local land use changes (like paving a road or building next to sensors or shelters) but not the slow ramp up characteristic of a growing town or city.

I had a conversation with NCDC's Tom Karl two years ago when the USHCN version 2 was announced. I told Tom I had endorsed his 1988 Journal of Climate paper (Urbanization: Its Detection and Effect in the United States Climate Record) having been a fan of the work that Landsberg and Oke on whose work that paper depended on.

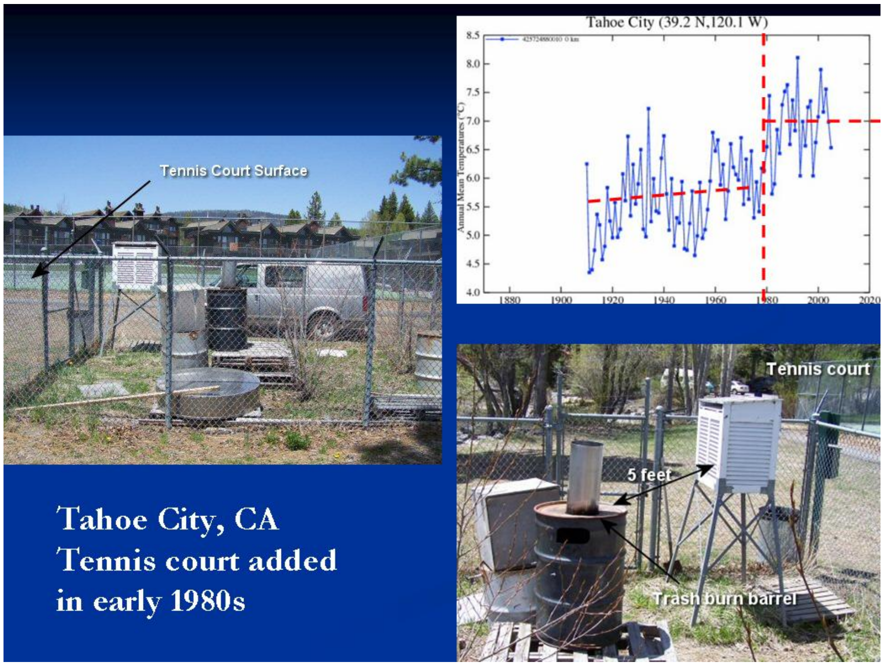
I asked him if USHCNv2 would no longer have an urbanization adjustment. After a few moments of silence, he told me he had asked those who had worked on version 2 that question and was reassured that the new algorithms would catch urban warming and other changes – including "previously undocumented inhomogeneities" (discontinuities that suggest some local site changes or moves that were never documented).

The difference between the old and new is shown here. Note the significant post 1995 warming and mid 20th century cooling due to deurbanization of the data base.



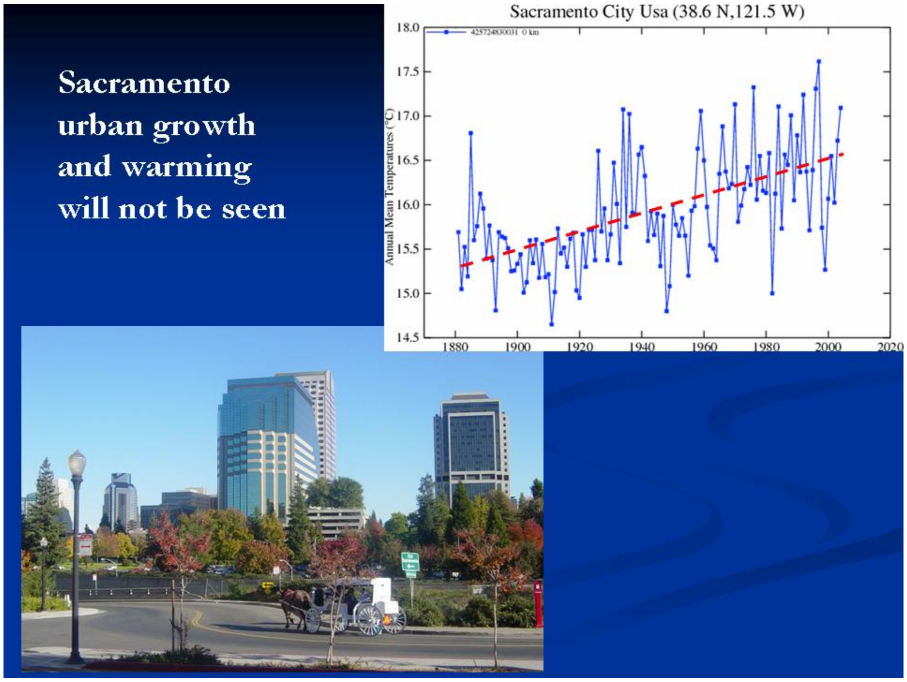
The change can be seen clearly in this animation.

The new algorithms are supposed to correct for urbanization, changes in siting and instrumentation by recognizing sudden shifts in the temperatures.



Tahoe City, CA
Tennis court added
in early 1980s

It should catch this kind of change above in Tahoe City, CA.

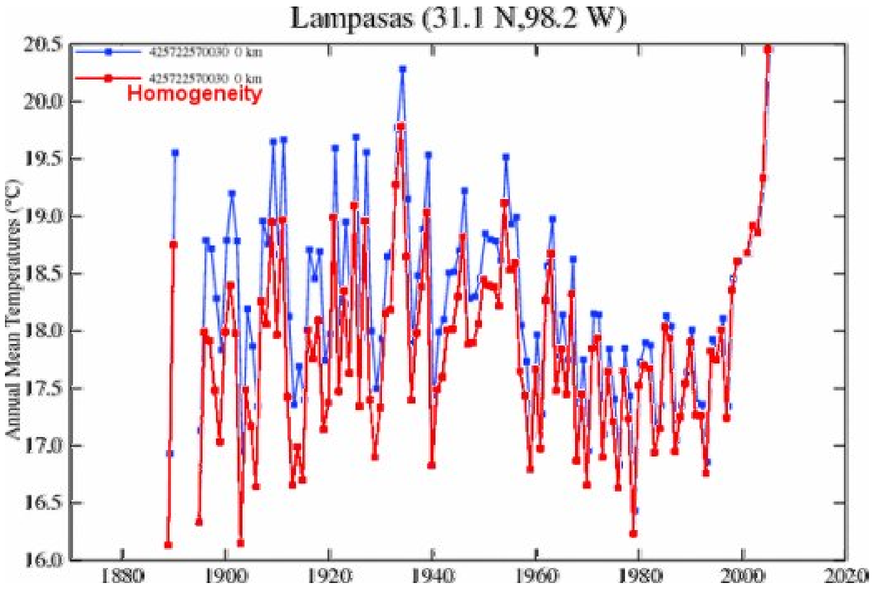


Sacramento
urban growth
and warming
will not be seen

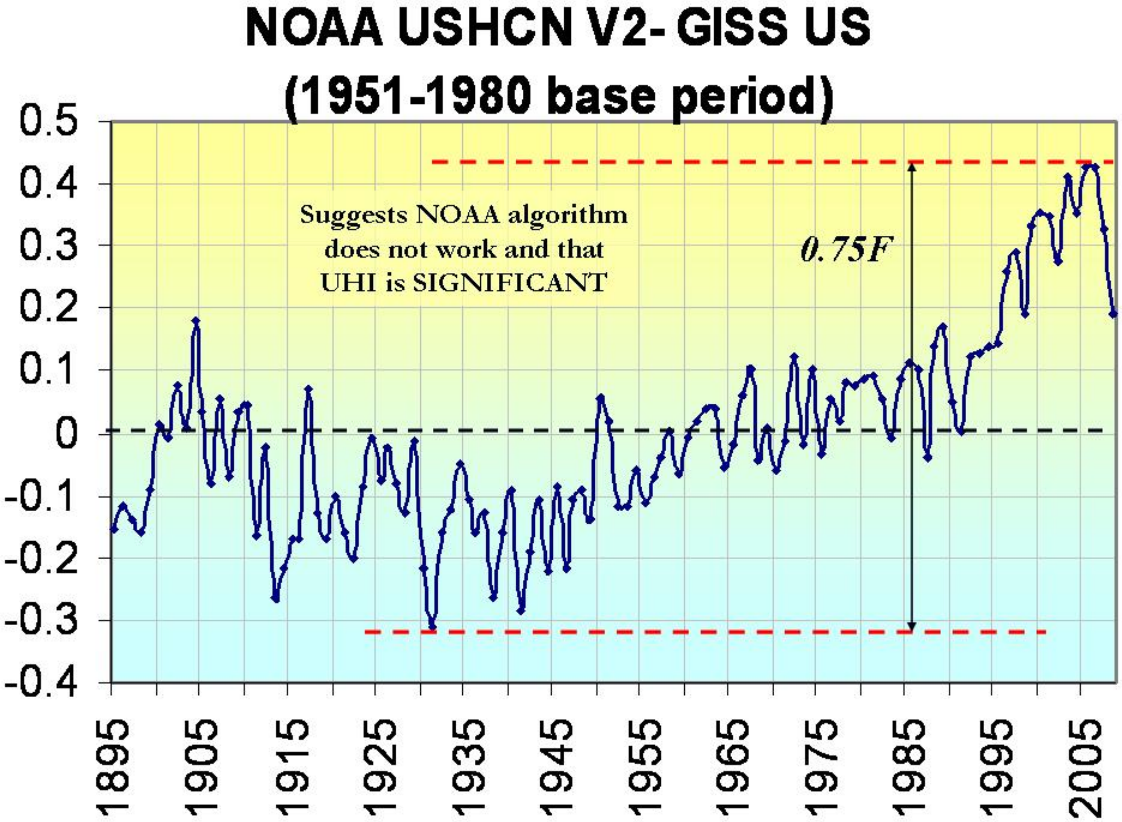
It is unlikely to catch the slow warming associated with the growth over many years of cities and towns as in Sacramento, CA above.

There is even some evidence that the algorithm does not catch some site changes it should catch. Take for example Lampasas, Texas as identified by Anthony Watts.

Lampasas, Texas site moved to near a building and street from a more appropriate grassy site after 2001. Note even with the new “homogeneity” adjustment (red) this artificial warming is left although the old data (blue) is cooled to accentuate warming even further.



The net result is to make the recent warm cycle max more important relative to the early century max in the 1930s.



Comparison of the new USHCN to the GISS USHCN which does a UHI adjustment based on night lights shows the NOAA version has increased the warming relative to the GISS by 0.75F since3 1930.

I asked Tom Karl about the problems with siting and why they could not speed up the plans for a Climate Reference Network (at that time called NERON). He said he had presented a case for that to NOAA but had it turned down with the excuse from high levels at NOAA that the surface stations did not matter <u>because we had satellite monitoring.</u> The Climate reference network was capped at 114 stations but won't provide meaningful trend assessment for about 10 years.

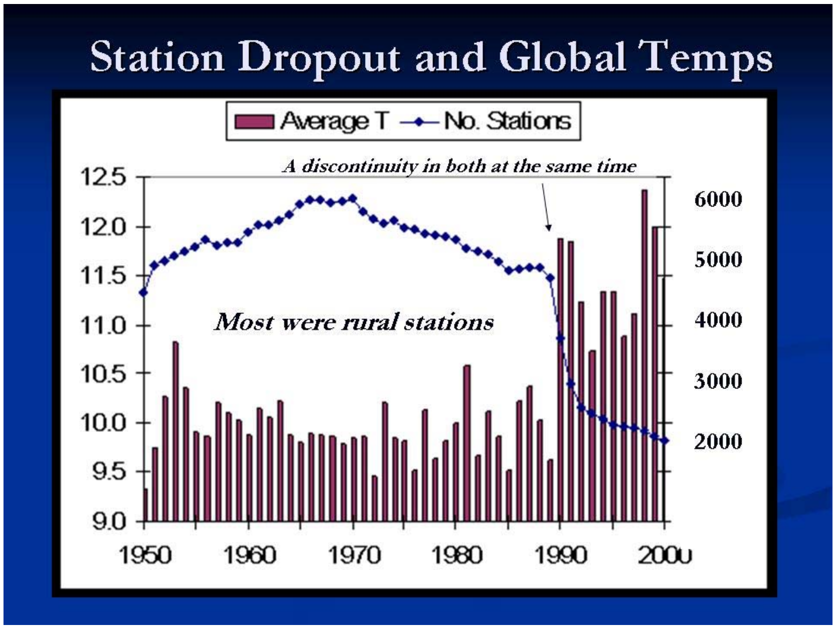
The NOAA attitude that the stations don't matter is manifested in the disregard for the siting as Anthony Watts has now with 2/3rds of the network surveyed found only 12 % satisfactory (3% CRN#1 and 9% CRN#2) and with no attempts to resolve the issues Anthony has found and presented to the NCDC staff. The change of the algorithms which worked fine was either an attempt to find an easy way to detect previously unrecorded site changes or to make the USHCN show more recent warming to be more in line with the global data bases. In monthly press releases, no satellite measurements are ever mentioned although NOAA claimed that was the future of observations.

THE GLOBAL DATA BASES

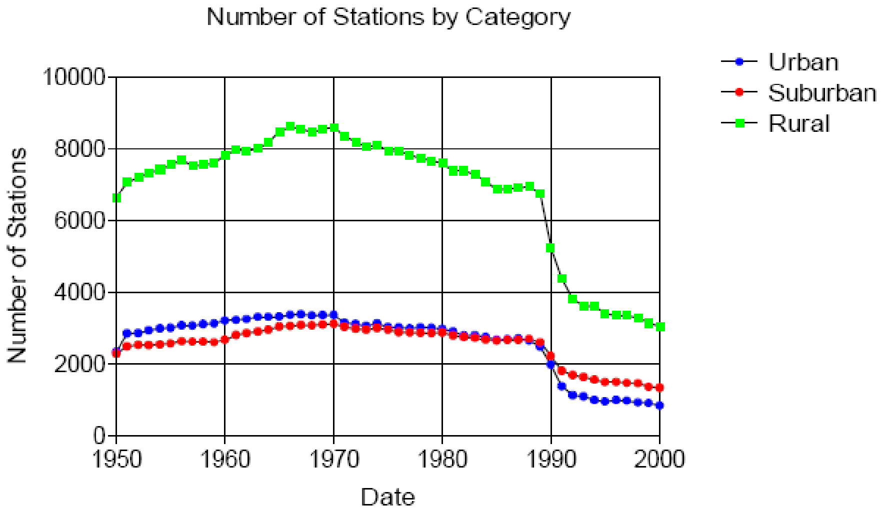
NOAA gathers global station and ocean ship data and makes it available for the NCDC GHCN and NASA GISS analyses. NCDC and NASA perform adjustments on this data, slightly different but generally similar in magnitude. They are hampered by issues in the global network which are greater in number and magnitude than for the United States.

STATION DROPOUT AND OTHER INTEGRITY ISSUES

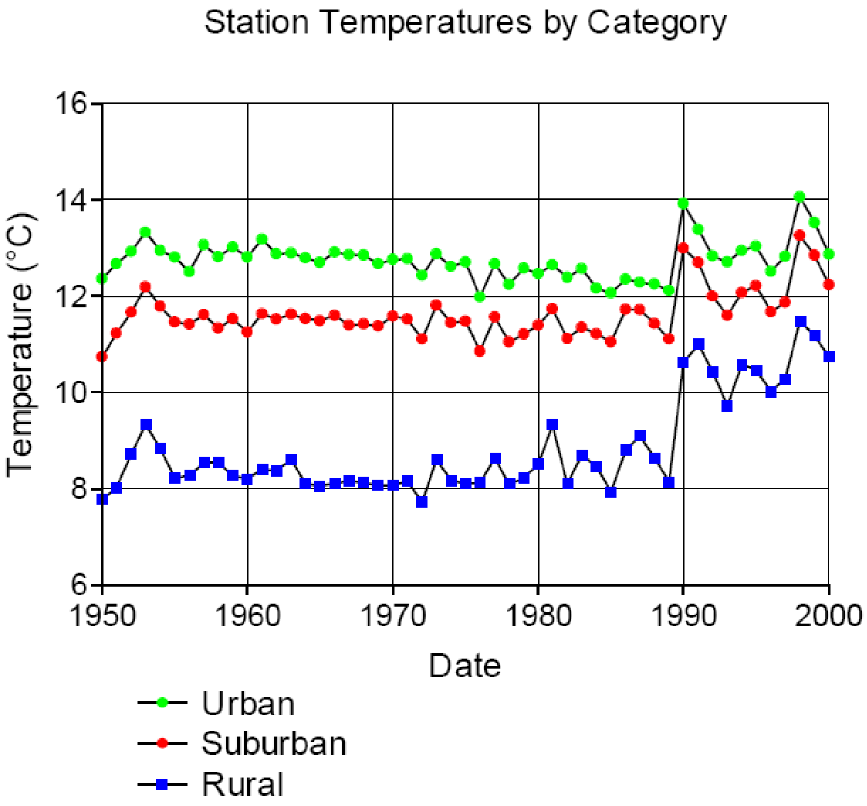
Globally a major issue is station dropout. Over 2/3rds of the world's stations, many of them rural areas in the former Soviet Union, stopped reporting around 1990. Dr. Kenji Matsuura and Dr. Cort J. Willmott at the University of Delaware has prepared this animation. See the lights go out in 1990. The animation shows that Siberia suffered the biggest station falloff.



In the chart above you see how this drop off of global sites coincides with a sudden rise in mean of all remaining stations. The analysis below of station count is broken down by rural, suburban and urban categories. It clearly shows a substantial drop in the number of rural stations. The numbers of stations are higher because many stations are given new numbers for every documented move or change.

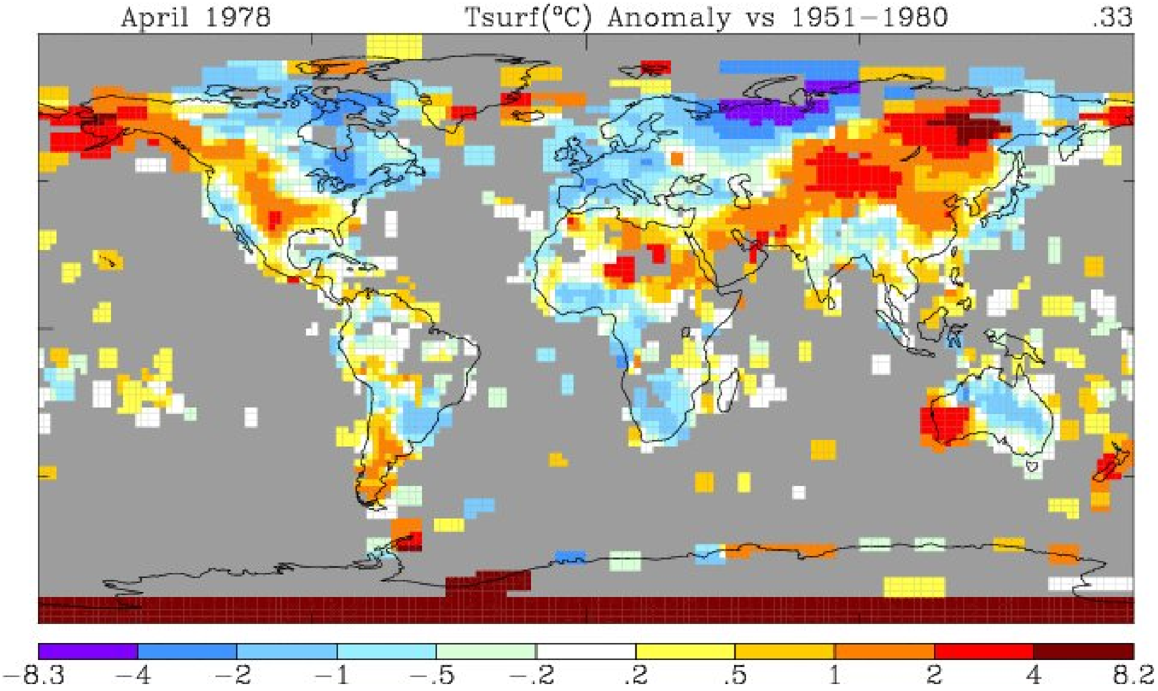


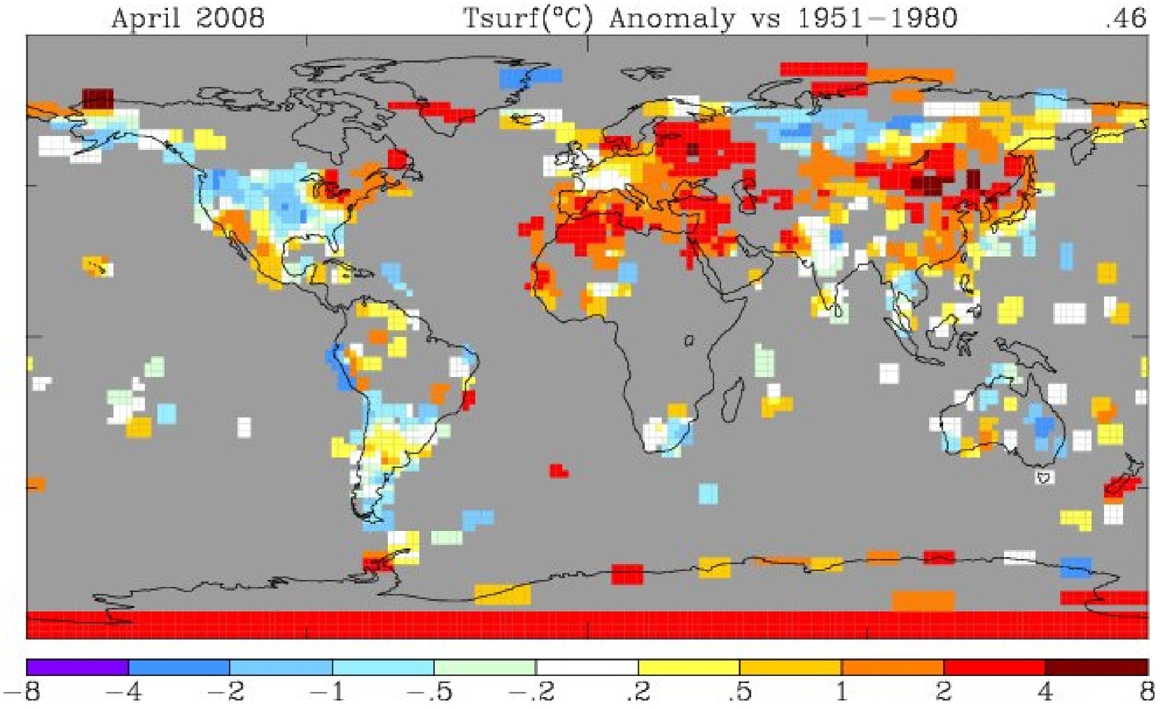
Average temperatures jumped when these other stations dropped out in all three categories but most notably in the rural data, suggesting that it was mainly colder, smaller, higher latitude stations that were no longer in the record (analyses above and below from Jonathan Drake)..



Global data bases all compile data into latitude/longitude based grid squares and calculate temperatures inside the square using data from the stations within it - or use the closest stations (weighted by distance) in nearby boxes. Thus a grid square, which at one time had rural stations, will find its mean temperature increasingly determined by the urban areas within that square or distant squares. This is why global data suggests that the greatest warming has occurred in Siberia, where the greatest dropout has occurred.

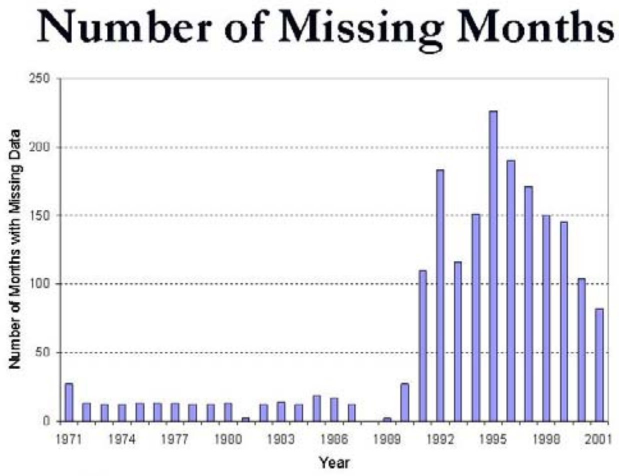
See the huge dropout of data in Africa, Canada and Siberia in the two maps from NASA GISS with 250 km smoothing from 1978 to 2008.





MISSING DATA INCREASES

In addition to station dropout, there has been a tenfold increase in missing months of data in places like the former Soviet Union.

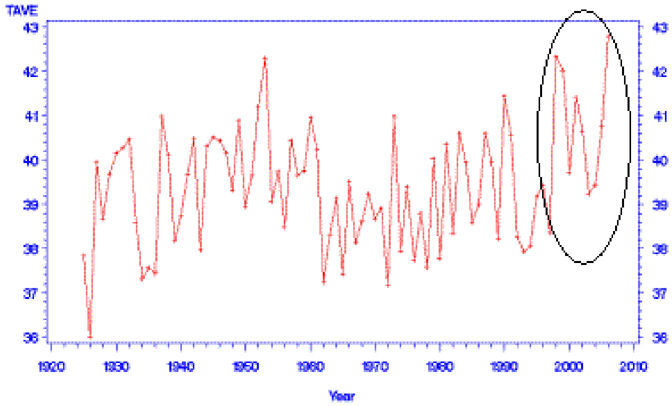


For the 110 Russian weather stations reporting weather data continuously from 1971 to 2001, the total number of missing monthly observations each year (McKitrick and Michaels)

For these stations that are missing periods or some stations that are now closed, surrounding stations are used. One example is Ripogenus Dam in Maine.

Last summer, volunteers completed surveys of the United States Historic Climate Network (USHCN) temperature stations in Maine for Anthony Watts surface station evaluation project. The survey determined that every one of the stations in Maine was subject to microclimate or urbanization biases. One station especially surprised the surveyors, Ripogenus Dam, a station that was officially closed in 1995.

Despite being closed in 1995, USHCN data for this station is publicly available until 2006!



USHCN 177174, RIPOGENUS DAM, ME
Annual mean of Monthly mean temperature (F) 1925 – 2006

Source: CN Williams Jr., MJ Menne, RS Vose, DR Easterling, NOAA, National Climatic Data Center, Asheville, NC

Part of the USHCN data is created by a computer program called “filnet” which estimates missing values. According to the NOAA, filnet works by using a weighted average of values from neighboring stations. In this example, data was created for a no longer existing station from surrounding stations, which in this case as we noted were all subject to microclimate and urban bias, no longer adjusted for. Note the rise in temperatures after this, perhaps before the best sited truly rural station in Maine was closed.

NO REAL URBAN ADJUSTMENT

HADLEY AND NOAA

Jones et al 1990 (Hadley CRU) concluded that UHI bias in gridded data could be capped at 0.05 deg C (not per decade, per century). Peterson et al (1998) agreed with the conclusions of Jones and Easterling *et al* (1997) that urban effects on 20th century globally and hemispherically-averaged land air temperature time-series do not exceed about 0.05°C over the period 1900 to 1990. Peterson (2003) and Parker (2004) argue urban adjustment thus is not really necessary. Yet recall Oke showed a town of 1000 could produce a 2.2C (3.4F warming).

The most recent exposition of CRU methodology is Brohan et al 2006, which stated with respect to UHI that they included an allowance of 0.1 deg C/century in the **uncertainty**, but does not describe any "correction" to the reported average temperature. To make an urbanization assessment for all the stations used in the HadCRUT dataset would require suitable meta-data (population, siting, location, instrumentation, etc) for each station for the whole period since 1850. No such complete meta-data are available.

The homepage for the NOAA temperature index here cites Smith and Reynolds (2005) as authority. Smith and Reynolds, in turn, state that they use the **identical** procedure as CRU, i.e. they make an allowance in uncertainty, but do not *correct* the temperature index itself. The population of the world went from 1.5 to 6.5 billion from 1900 to 2000, yet NOAA and CRU ignore population growth in the data base with only a 0.1C uncertainty adjustment.

Runnalls and Oke (2006) concluded that “Gradual changes in the immediate environment over time, such as vegetation growth, or encroachment by built features such as paths, roads, runways, fences, parking lots, and buildings into the vicinity of the instrument site typically lead to trends in the series.

Distinct régime transitions can be caused by seemingly minor instrument relocations (such as from one side of the airport to another, or even within the same instrument enclosure) or due to vegetation clearance.

This contradicts the view that only substantial station moves, involving significant changes in elevation and/or exposure are detectable in temperature data.”

More than half dozen peer reviewed papers found that the lack of adequate UHI and local land use change adjustments could account for up to 50% of the warming since 1900.

In the areas of greatest warming, Siberia, besides dropout and a tenfold increase in missing monthly data, there were numerous issues related to prior temperatures In the Soviet era. city and town temperatures determined allocations for funds and fuel, so it is believed that cold temperatures were exaggerated in the past, which introduced an apparent warming when more honest measurements began to be made. Also Anthony Watts has found that in many Russian towns and cities, heating pipes are in the open. Any sensors near these pipes would be affected.

GISS GLOBAL

Is NASA better? Steve McIntyre has taken an in-depth look at the data adjustments made to NASA's GISS data set. The findings are summarized very well in Ken Gregory of Friends of Science’s “*Correct the Correction*”.

> “NASA’s Goddard Institute of Space Studies (GISS) publishes a global temperature index. The temperature record is contaminated by the effects of urban development and land use changes. NASA applies an “urbanization adjustment” to adjust the temperature histories to eliminate these effects. The resulting GISS temperature index is supposed to represent what the temperatures would have been in the absence of urbanization and land use changes. Most scientists assume that these adjustments are done correctly.

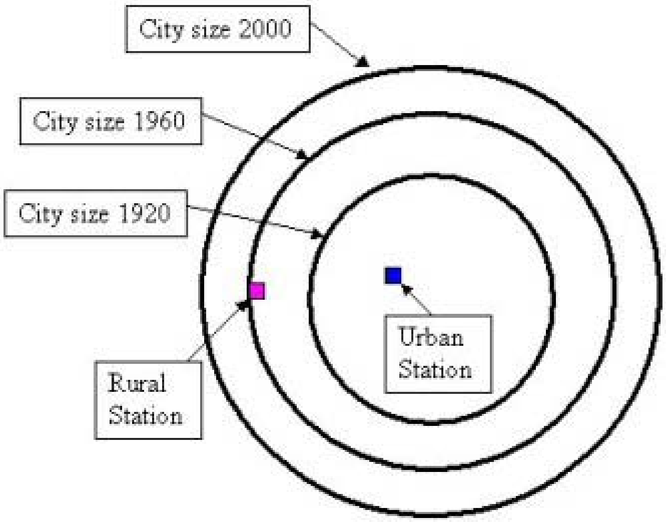
An audit by researcher Steve McIntyre reveals that NASA has made urban adjustments of temperature data in its GISS temperature record in the wrong direction. The urban adjustment is supposed to remove the effects of urbanization, but the NASA negative adjustments increases the urbanization effects. The result is that the surface temperature trend utilized by the International Panel on Climate Change (IPCC) is exaggerated.

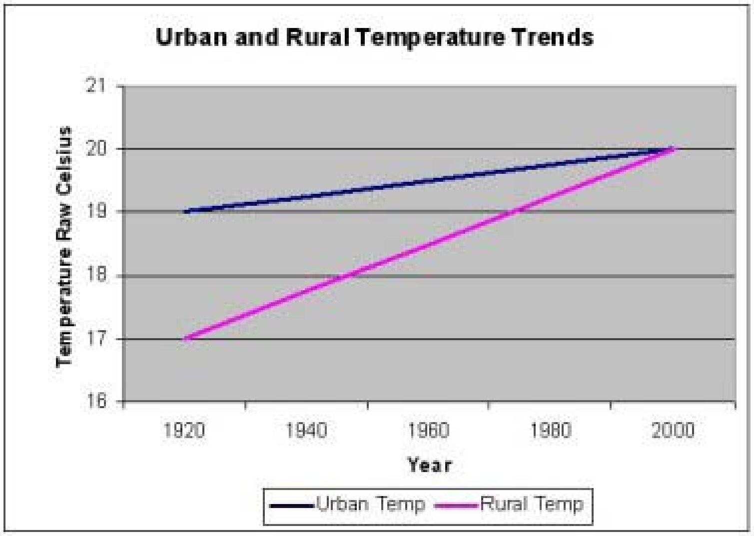
“Outside of the USA, southern Canada and northern Mexico, GISS uses population data to define rural stations. “We use the definition of Peterson et al 1997 for these categories: that is, rural areas have a recent population of less than 10,000, small towns between 10,000 and 50,000 and urban areas more than 50,000. These populations refer to approximately 1980.”

The GISS sites are defined to be “rural” if the town has a population of under 10,000. Unfortunately, the population data utilized by GISS to classify the stations is out of date. Stations at cities with populations greatly exceeding 10,000 are incorrectly classified as rural. For example, in Peru, there are 13 stations classified as rural. Of these, one station is located at a city with a population of 400,000. Five stations are at cities with populations between 50,000 and 135,000.

Steve McIntyre says here, “If the supposedly “rural” comparanda are actually “urban” or “small towns” within the Hansen definitions, then the GISS “adjustment” ends up being an almost completely meaningless adjustment of one set of urban values by another set of urban values. No wonder these adjustments seem so random.”

A population increase of 500 in a town of 2000 people would have a much larger effect on temperature measurements than the same increase in a city of 500,000 people. A city with a growing population generally increases its area. A temperature station inside the city would be little affected by the expansion of the suburbs. However, a temperature station located just outside a city would be greatly affected by the city expanding around the station. This effect is shown in the following diagram.

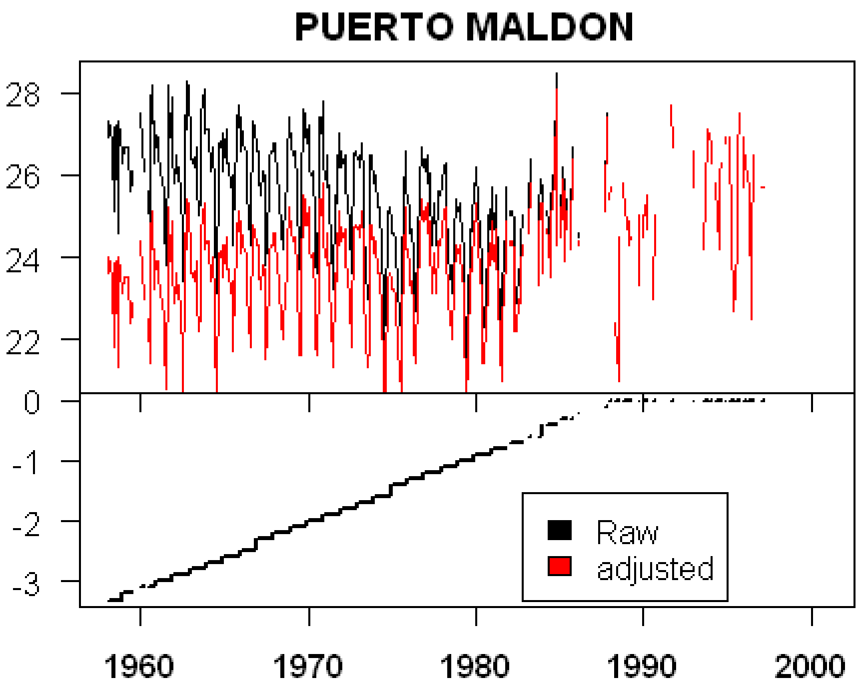




A hypothetical urban station is shown located in a city and a rural station is located outside the city in the year 1920. By 1960, the city has grown out to the rural station. The city growth has little effect on the urban station, but a much larger affect on the rural station. By 2000, the rural station is completely surrounded by the city, so it has the same temperature as the urban station...

Now, as indicated in the graph, the unadjusted rural temperature trend is much greater than the urban station trend. ***According to the GISS urban adjustment procedure, the urban station trend is increased to match the rural station trend by reducing the past temperatures.***

Here is an example of an urban negative adjustment from Peru:



Note that the raw data shows no warming, but after applying the GISS urban adjustment, the adjusted data shows a significant warming trend. The adjustments are applied to reduce the past temperatures by up to 3 degrees Celsius. This is a very large adjustment when compared to the total warming of the twentieth century of 0.6 Celsius estimated by the IPCC.

A proper urban correction algorithm would reduce the warming trends of both stations to make an adjusted temperature record represent what would have happened if nobody lived near the stations.

Ross McKitrick and Patrick Michaels in December 2007 showed a strong correlation between urbanization indicators and the "urban adjusted" temperatures, indicating that the adjustments are inadequate. Their conclusion is: "Fully correcting the surface temperature data for 'non-climatic effects reduce the estimated 1980-2002 global average temperature trend over land by about half."

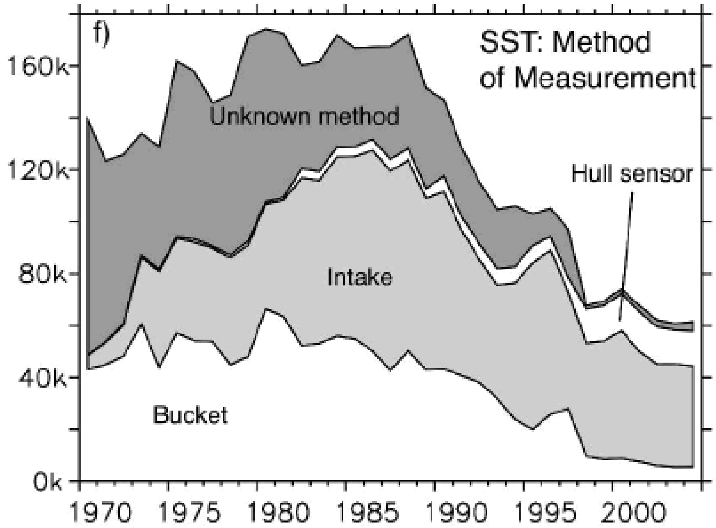
Dutch meteorologists, Jos de Laat and Ahilleas Maurellis, showed (2006) that climate models predict there should be no correlation between the spatial pattern of warming in climate data and the spatial pattern of industrial development. But they found that this correlation does exist and is statistically significant. They also concluded it adds a large upward bias to the measured global warming trend.

These studies convincingly show that urban "corrections" fail to correct for the effects of urbanization, but do not indicate why the corrections fail. The audit of GISS urban adjustments by Steve McIntyre shows why the corrections fail. "

A2008 paper by Hadley's Jones etal, has shown a considerable contamination in China, the equivalent of 1F per decade, an order of magnitude greater than the amount previously assumed (0.1F uncertainty). This vindicates our position on the UHI issue.

OCEANS HAVE ISSUES TOO

The world is 70% ocean. Hadley only trusts their own merchant ship data, mainly derived from northern hemisphere routes. Hadley has virtually no data from the southern hemisphere's oceans (80% of the hemisphere). NOAA and NASA use ship data reconstructions. The gradual change of buckets to ship intakes for taking ocean temperature measurements introduces uncertainties. Different sampling levels will make results slightly different. How to adjust for this introduced difference and get reliable data set has yet to be resolved adequately, especially since the transition occurred over many decades. *Chart from Kent (2007).*



We have reanalysis data based on reconstructions from ships and buoys (subject to some of the same adjustment issues) and satellites which see only ocean surface skin temperatures but are hampered by cloud cover. That data was removed by NOAA in July 2009 because of alleged "complaints" about a cold bias in the southern hemisphere. Immediately the results was a bump up of ocean and ocean/land global temperatures and the warmest ever July and August for the world's oceans.

SUMMARY

The United States and global data bases have serious problems that render them highly questionable for determining accurate long term temperature trends. Especially since most of the issues mentioned produces a warm bias in the data.

As shown here, though there has clearly been some cyclical warming in recent decades (most notably 1979 to 1998), the global surface station based data is seriously compromised by urbanization and other local factors (land-use/land-cover, improper siting, station dropout, instrument changes unaccounted for and missing data) and uncertainties in ocean temperatures. Thus the data bases can't be relied on to determine accurate trends. These factors all lead to overestimation of temperatures. Numerous peer-reviewed papers (referenced below in bold) in the last several years have shown this overestimation is the order of 30 to 50% from these issues alone.

See my and other relevant presentations and videos of some excellent keynote addresses at the Second Annual ICCC in New York City March 8-10, 2009 here.

References:

Block, A, Keuler, K., Schaller, E., 2004, Impacts of anthropogenic heat on regional climate patterns, Geophysical Research Letters, 31, L12211, DOI:10.1029/2004GL019852

Brohan, P., J.J. Kennedy, I. Harris, S.F.B. Tett and P.D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. J. Geophysical Research ***111****, D12106, DOI:10.1029/2005JD006548*

Davey, C.A., and R.A. Pielke Sr. (2005) "Microclimate Exposures of Surface-based Weather Stations - Implications for the Assessment of Long-term Temperature Trends." Bulletin of the American Meteorological Society 86(4) 497–504

de Laat, A.T.J., and A.N. Maurellis (2006). "Evidence for Influence of Anthropogenic Surface Processes on Lower Tropospheric and Surface Temperature Trends." International Journal of Climatology 26:897—913.

Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Folland CK (1997) Maximum and minimum temperature trends for the globe. Science 277:364-367

Gall, R, Young, K., Schotland, R, Schmitz, J.: 1992. The Recent Maximum temperature Anomalies In Tucson. Are they real or an Instrument Problem, Journal of Climate, 5, 657-664.

Goodridge, JD (1996) Comments on "Regional Simulations of Greenhouse Warming including Natural Variability" . Bull, Amer. Meteorological Society 77:1588-1599

Hansen, J., Ruedy, R., Glascoe, J. and Sato, M. 1999. GISS analysis of surface temperature change. Journal of Geophysical Research 104: 30,997-31,022

Hansen, J, R. Ruedy, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl, 2001: A closer look at United States and global surface temperature change. Journal of geophysical research, 106 (D20), 23947-23963.

Hinkel, K.M., Nelson, F.E., Klene, S.E., Bell, J.H.:(2003). The Urban Heat Island In Winter At Barrow, Alaska, International Journal Of Climatology. ***23****: 1889–1905, DOI: 10.1002/joc.971*

Jones, C.G., Young , K.C.,:)1995) An Investigation of Temperature Discontinuities Introduced by the Installation of the HO-83 Thermometer Journal of Climate Volume 8, Issue 5 (May 1995) pp. 1394

Jones PD, Groisman PYa, Coughlan M, Plummer N, Wangl WC, Karl TR (1990) Assessment of urbanization effects in time series of surface air temperatures over land. Nature 347:169-172

Jones, P. D., D. H. Lister, and Q. Li (2008), Urbanization effects in large-scale temperature records, with an emphasis on China, J. Geophys. Res., 113, D16122, doi:10.1029/2008JD009916.

Kalnay, E., Cai, M., Impacts of urbanization and land-use change on climate, 2003, Nature, 423, 528-531

Karl, T.R., H.F. Diaz, and G. Kukla, 1988: Urbanization: its detection and effect in the United States climate record, J. Climate, ***1****, 1099-1123*

Karl, T.R, 1995: Critical issues for long-term climate monitoring. Climate Change, 31, 185.

Kent, E. C., S. D. Woodruff, and D. I. Berry. 2007. Metadata from WMO Publication No. 47 and an Assessment of Voluntary Observing Ship Observation Heights in ICOADS. Journal of Atmospheric and Oceanic Technology 24, no. 2: 214-234

Landsberg, H.E., 1981: The Urban Climate, Academic Press

Li, Q. et al., 2004: Urban Heat Island Effect on Annual Mean Temperatures during the Last 50 Years in China. Theor. Appl. Climatol., 79, 165-174.

McKitrick, R.R. and P.J. Michaels (2007), Quantifying the influence of anthropogenic surface processes and inhomogeneities on gridded global climate data, J. Geophys. Res., 112, D24S09, doi:10.1029/2007JD008465.

McKitrick, R and P. J. Michaels (2004). “A Test of Corrections for Extraneous Signals in Gridded Surface Temperature Data” Climate Research 26(2) pp. 159-173. “Erratum,” Climate Research 27(3) 265—268.

Moberg, D. and A. 2003. Hemispheric and Large-Scale Air Temperature Variations: An Extensive Revision and Update to 2001. Journal of Climate, 16, 206-223.

Oke, T.R. 1973. City size and the urban heat island. Atmospheric Environment ***7****: 769-779.*

Parker, D.E. (2004). "Climate: Large-Scale Warming is not Urban." Nature 432, 290 (18 November 2004); DOI:10.1038/432290a

Peterson T.C. and R.S. Vose (1997) "An Overview of the Global Historical Climatology Network Temperature Database." *Bulletin of the American Meteorological Society* 78:2837—2849.

Peterson, T.C. (2003). "Assessment of Urban Versus Rural in situ Surface Temperatures in the Contiguous United States: No Difference Found." Journal of Climate 16(18) 2941—2959.

Peterson, 2006 Examination of potential biases in air temperature caused by poor station locations. Bull. Amer. Meteor. Soc., 87, 1073-1089

Pielke Sr., R.A., C. Davey, D. Niyogi, S. Fall, J. Steinweg-Woods, K. Hubbard, X. Lin, M. Cai, Y.-K. Lim, H. Li, J. Nielsen-Gammon, K. Gallo, R. Hale, R. Mahmood, S. Foster, R.T. McNider, and P. Blanken, 2007: Unresolved issues with the assessment of multi-decadal global land surface temperature trends. J. Geophys. Res., 112, D24S08, doi:10.1029/2006JD008229

Pielke Sr., R.A. J. Nielsen-Gammon, C. Davey, J. Angel, O. Bliss, N. Doesken, M. Cai., S. Fall, D. Niyogi, K. Gallo, R. Hale, K.G. Hubbard, X. Lin, H. Li, and S. Raman, 2007: Documentation of uncertainties and biases associated with surface temperature measurement sites for climate change assessment. Bull. Amer. Meteor. Soc., 88:6, 913-928.

Runnalls, K.E. and Oke, T.R. 2006. A technique to detect microclimatic inhomogeneities in historical records of screen-level air temperature. Journal of Climate ***19****: 959-978.*

Smith, T. M., and R. W. Reynolds (2004), Improved extended reconstruction of SST (1854-1997), J. Climate, ***17****, 2466-2477.*

Smith, T. M., and R. W. Reynolds (2005), A global merged land air and sea surface temperature reconstruction based on historical observations (1880-1997), J. Climate, ***18****, 2021-2036*

Zhou, L., Dickinson, R, Tian, Y., Fang, J, Qingziang, L., Kaufman, R, Myneni, R., Tucker, C., 2004, Rapid Urbanization warming China's climate faster than other areas, Proceedings of the National Academy of Science, June 29, 2004

Appendix B

Snohomish County
Public Works

Aaron Reardon
County Executive

3000 Rockefeller Ave., M/S 607
Everett, WA 98201-4046

(425) 388-3488
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March 30, 2010

Electronic comments submitted via email to Leif Hockstad at hockstad.leif@epa.gov

Mr. Leif Hockstad
Environmental Protection Agency
Climate Change Division (6207J)
1200 Pennsylvania Ave., NW
Washington, DC 20460

Dear Mr. Hockstad:

Thank you for the opportunity to submit comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008.

I served in support of and as the alternate for Executive Aaron Reardon in his role as an appointed member of the Governor's Climate Action Team (CAT). I also served as co-chair of the Beyond Waste Implementation Work Group of the Washington State CAT and have assisted in the development of our local Snohomish County GHG inventory and climate action plan.

Through all of this work, a consistent problem has been the misimpression of the importance (or lack thereof) of addressing material management, due to the inventory methodology, explanation, and presentation. Because the inventories do not use or present a systems or consumption-based view, decision makers and planners see local, state and national inventories that show a scant 2-4% of green house gases attributed to "waste". The result is that addressing "waste" is considered immaterial or minimized, and "waste" discussions and strategies, if considered at all, are lumped with other incompatible sectors, such as agriculture and forestry, and are given few resources and little time.

This is quite a problem and you can find it reflected in most state and local inventories and climate action plans.

I am often asked to speak to local groups, such as Climate Stewards or Carbon Masters about "waste". I have attached several of my power point slides from a recent presentation. At these presentations, I usually begin by apologizing for what a terrible mistake the organizers have made in inviting me. "If you are a decision maker who has looked at the national, state or local inventories, you know that waste isn't relevant" (and I show the corresponding pie charts). Then I show the alternate pie charts based off of EPA's recently published report, *Opportunities to Reduce Greenhouse Gases Through Materials and Land Use Management* and the Product Policy Institute's White Paper on the same subject, to reframe what I am talking about and its importance. I receive strong positive feedback for providing this clarification about what the inventories show us, or don't.

The Washington State Inventory can be viewed at:
http://www.ecy.wa.gov/climatechange/docs/Updated1990GHGreport20071219.pdf

You can read the summary related to "waste" on page 5 (ES-3). You can see the summary on "data gaps and unresolved questions" on page 6 (ES-4). In neither case is there any indication that the inventory methodology does not address the issue of material management and consumption in a way that can be translated to policy and programmatic actions. This is despite providing comment to the consultants developing the report, who though sympathetic and recognizing the problem, stated that currently accepted inventory protocols did not provide for a systems or consumption view. You can see under the "waste" Appendix G that we were unsuccessful in getting any reference to the limits of what this type of inventory shows related to consumption and managing of materials (products and packaging for instance). The text explains what the inventory covers, but fails to state what it doesn't include (all upstream impacts related to in-state consumption of resources).

This immediately created confusion with some stakeholders and particularly entrenched interests, who protested the need to even address waste at all in the climate action plan and strategy process, as the inventory showed that there was no GHG implications to simply land filling most materials, "waste" was insignificant, and addressing "waste" strategies would be a distraction from addressing the "important" areas generating GHGs.

Fortunately, due to a clearer understanding by our Department of Ecology on GHG implications of material management and upstream impacts, we were able to prioritize further work on materials management. The Beyond Waste Implementation Work Group (BW IWG) became one of four IWGs formed to develop early action recommendations and key strategies and legislative proposals for the CAT.

The next challenge resulting from the inventory's methodology and lack of clarity on what it does and doesn't document, was that stakeholders and many CAT members did not initially believe the significant GHG reductions that could be achieved through some of the strategies recommended by the BW IWG. These strategies can be seen at http://www.ecy.wa.gov/climatechange/2008CATdocs/ltw_app_v2.pdf , Appendix 5. They questioned how it could be possible to accomplish such significant GHG reductions, more so than some of the key transportation and energy related recommendations, when "waste" resulted in such a small percent of GHG emissions to start with. Again, the lack of providing clarity on what the current protocol does and doesn't do, what alternative views would show, and implications, was quite a road block. The CAT, BW IWG and our consultants struggled with how to address this.

You will see on pages 51 and 52 that we developed a chart that showed in-state emissions that "counted" and out-of-state emissions that didn't "count" but were critical. Note the explanatory text in the footnote on page 51.

Similar challenges resulted from the locally developed inventory, using ICLEI's methodology.

The Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008* repeats these inadequacies and will replicate our state and local challenges in appropriately addressing materials management through policy and programs many times over. It is not enough to simply provide the inventory without regard to how inventories are used and understood. It is not adequate to state what the inventory does – the document needs to explain what it doesn't do, what alternate methodologies might show, and implications for policy makers and climate change program planners.

In the draft inventory, you have included an alternative sector view, using Economic Sectors. I think this is useful, and hope that you do the same for a systems or consumption based view. As the Economic Sector approach completely eliminates reference to a "waste" sector, I don't know if this will result in even less attention to upstream material management strategies or open up those strategies for more robust consideration by not pigeon-holing them under "waste".

I have also personally found it confusing that the global warming potentials that are required to be used are 100 year potentials. When I make presentations, I cringe at questions from the public who are interested in knowing that we and they can respond quickly, when it looks like some of our methodologies don't really show impacts during the correct time frames. It would be helpful to provide additional information on other warming potential time frames.

For these reasons, I recommend the following:

1. The US Inventory should integrate a systems-based or consumption-based view and present it alongside the sector-based view. Even if a detailed analysis is not available, providing text and graphics that demonstrate how an alternate view provides valuable information for policy and program development would be tremendously helpful to the public, stakeholders, policy makers and planners. Coupled with the traditional sector-based view, the systems-based view offers a much more comprehensive perspective on how the US contributes to GHG emissions. At the very least this should be included under "planned improvements" in the waste section.

2. Consumption-related emissions should be formally acknowledged in the US Greenhouse Gas Inventory. The US Greenhouse Gas Inventory should be much more explicit in stating that the inventory is limited to emissions that physically originate within the national borders of the US. It should explain that the US also contributes to emissions that are counted in the inventories of other nations, as a consequence of imports. The emissions associated with US exports are less than those associated with US imports. When viewed from the perspective of consumption, the greenhouse gas impact of the US is higher than suggested by the traditional IPCC accounting standard. This is of great importance: consumption is the root cause of emissions. Until this is clearly explained and addressed, stakeholders, policy makers and planners will not understand the key overarching strategy of reducing consumption of energy and resources.

3. Please include both 100-year, and 20-year global warming potentials (GWPs) in the Inventory. While the Inventory points out that other GWPs are also available, it would be more useful to actually include that analysis in the Inventory to assist policymakers, planners and stakeholders.

These changes would make the inventory more understandable and useful at the both the state and local level, and would be a first step in moving inventories at all levels to providing a more comprehensive analysis.

Thank you for the chance to comment.

Sincerely,

Sego Jackson
Principal Planner
Snohomish County Solid Waste Division

Appendix C

United States Department of the Interior

NATIONAL PARK SERVICE
Environmental Quality Division
P.O. Box 25287
Denver, CO 80225-0287

IN REPLY REFER TO:

ELECTRONIC TRANSMISSION ONLY – NO HARD COPY TO FOLLOW
April 13, 2010

(2310)

Docket ID No. FRL-9126-3
Leif Hockstad
Environmental Protection Agency
Climate Change Division (Mailcode 6207J)
1200 Pennsylvania Avenue, NW
Washington, D.C. 20460

Dear Mr. Hockstad

These comments are submitted on behalf of the National Park Service (NPS) in response to the U.S. Environmental Protection Agency's (EPA) March 15, 2010, Federal Register Notice requesting review and comment on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008.

EPA produces an annual inventory of greenhouse gas emissions and sinks using methodologies that are consistent with those recommended by the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (most recently updated in 2006). This allows U.S. emissions to be directly compared with inventories of other nations participating in the United Nations Framework Convention on Climate Change. Each year, emissions and sinks are recalculated for all years in the inventory from 1990 to the current year, to incorporate improvements in emissions methods and data.

Separately, under the Executive Order "Federal Leadership in Environmental, Energy, and Economic Performance" issued in October 2009, federal agencies are now required to "measure, report, and reduce their greenhouse gas (GHG) emissions from direct and indirect activities." The Department of Energy (DOE) Federal Energy Management Program (FEMP) in cooperation with other federal agencies has developed the Federal Greenhouse Gas Accounting and Reporting Guidance to define methods for reporting emissions. EPA should ensure that methods used in this annual inventory of greenhouse gas emissions and sinks are consistent with the FEMP methodologies. If source categories or reporting methods differ, it would be appropriate to define the basis for differences in a new section added to this report.

The inventory results are informative and for the most part clearly presented. While we agree that currently available methods make it difficult to specifically quantify the impacts of forest fires on net carbon sequestration in forests, EPA should acknowledge the numerous efforts by federal agencies to improve methods to characterize fire emissions. Future inventories may be able to refine these estimates.

For further information, please contact Pat Brewer, Air Resources Division, at 303-969-2153.

Sincerely,

/s/ Joe Carriero
External Affairs Program Manager
Environmental Quality Division

cc:
Patricia Brewer, NPS Air Resources Division
Julie Thomas NPS McNamee, Air Resources Division
John Bunyak, NPS Air Resources Division

Appendix D

BIOMASS ACCOUNTABILITY PROJECT • CENTER FOR BIOLOGICAL DIVERSITY • ENERGY JUSTICE NETWORK • GLOBAL ALLIANCE FOR INCINERATOR ALTERNATIVES • GREEN BERKSHIRES • MASSACHUSETTS FOREST WATCH

April 14, 2010

Via email: hockstad.leif@epa.gov and regulations.gov

Leif Hockstad
Environmental Protection Agency
Climate Change Division (6207J)
1200 Pennsylvania Ave., NW
Washington, DC 20460

Re: Inventory of U.S. Greenhouse Gas Emissions and Sinks

Dear Mr. Hockstad:

The undersigned organizations respectfully submit the following comments on the United States Environmental Protection Agency's ("EPA") Inventory of U.S. Greenhouse Gas Emissions and Sinks (the "Inventory").

EPA's inventory document repeats a pernicious assumption that has profound consequences for both the climate and the nation's forests: the assumption that biomass combustion is "carbon neutral." EPA recognizes, as it must, that the combustion of biomass and biofuels produces CO_2 and other greenhouse gases. Yet EPA declines to include these emissions in national totals "because biomass fuels are of biogenic origin."[1] According to EPA, "[i]t is *assumed* that the carbon (C) released during the consumption of biomass is recycled as U.S. forests and crops regenerate, causing no net addition of CO_2 to the atmosphere."[2]

As described in detail below, scientists have concluded that this assumption represents a critical error in EPA's climate accounting methodology. This error pervades all of EPA's biomass calculations, but it is especially glaring as applied to facilities that burn woody biomass from tree plantations, forest thinning projects, or fire salvage projects. Promotion of new and expanded biomass energy facilities predicated on this assumption is beginning to threaten both the ecology of the nation's forests and the stability of the world's climate. EPA thus should revise the Inventory to eliminate reliance on the "carbon neutrality" assumption and should adopt accounting methods that

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[1] U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2008; Public Review Draft (March 9, 2010), Ch. 3 (Energy) at 1.
[2] *Id.* (emphasis added).

accurately measure emissions from both biomass combustion and associated land use change on time scales relevant to climate protection efforts.

I. Scientists Have Identified Critical Errors in EPA's Carbon Accounting Methods.

Recent scientific work has identified a "critical climate accounting error" in the EPA's inventory method: namely, its failure to account accurately for carbon emissions associated with biomass and biofuels in the land use sector.[3] Specifically, EPA's accounting "erroneously treats all bioenergy as carbon neutral regardless of the source of the biomass, which may cause large differences in net emissions. For example, the clearing of long-established forests to burn wood or grow energy crops is counted as a 100% reduction in energy emissions despite causing large releases of carbon."[4]

Energy generated from biomass reduces greenhouse gas emissions "only if the growth and harvesting of the biomass for energy captures carbon above and beyond what would be sequestered anyway."[5] Scientists thus believe that the better solution is to focus first on carbon emissions from the smokestack, and then to factor in emissions and reductions associated with land use change. According to Searchinger, et al. (2009):

> The straightforward solution is to fix the accounting of bioenergy. That means tracing the actual flows of carbon and counting emissions from tailpipes and smokestacks whether from fossil energy or bioenergy. Instead of an assumption that all biomass offsets energy emissions, biomass should receive credit to the extent that its use results in additional carbon from enhanced plant growth or from the use of residues or biowastes. Under any crediting system, credits must reflect net changes in carbon stocks, emissions of non-CO_2 greenhouse gases, and leakage emissions resulting from changes in land-use activities to replace crops or timber diverted to bioenergy.[6]

Such accounting also must include site-specific and regional analysis of energy generation, distribution, consumption, and demand trends sufficient to support any conclusion that biomass generation will actually offset fossil-fired generation. As discussed below, moreover, proper accounting also demands that the short-term impacts of biomass combustion be considered especially significant in light of the long time period required for resequestration of released carbon. Accurate accounting is absolutely critical to determining whether smokestack emissions from biomass combustion can be treated as "carbon neutral" in the manner proposed by EPA.

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[3] Timothy Searchinger, et al., *Fixing a Critical Climate Accounting Error*, 326 SCIENCE 527 (2009).

[4] *Id.* at 527. As described in more detail below, this error is not limited to situations where forests are cleared entirely or converted to energy crops; rather, this error also infects analysis of the carbon impacts of thinning existing forests for biomass fuels.

[5] *Id.* at 528.

[6] *Id.*

II. The Carbon Neutrality Assumption Ignores the Critical Time Lapse Between Present Carbon Dioxide Emissions and Future Carbon Sequestration.

The claim that biomass combustion is "carbon neutral" because biomass is "biogenic" is both false and dangerous, primarily because it ignores the fact that carbon emitted during biomass combustion may remain in the atmosphere for decades or centuries before being resequestered. The claim thus ignores the critical temporal relationships between present carbon emissions and the future effects of global warming and climate change. In other words, because meeting (or exceeding) atmospheric CO_2 targets has a strong temporal element, the time that it takes for CO_2 released into the atmosphere today to be reabsorbed is of critical importance in assessing the climate impacts of carbon emissions, regardless of their "biogenic" origin.

Scientists agree that "[t]he amount of carbon sequestered by forest ecosystems plays an important role in regulating atmospheric levels of carbon dioxide."[7] The removal and processing of forest biomass reduces storage in forest carbon pools and results in short-term emissions of greenhouse gases, even when some of that biomass remains sequestered for a period of time in commercial forest products.[8] According to recent studies, "[t]ypically 30–50% of the harvested C is lost in manufacturing and initial use, a loss that is larger than could be expected from even the most extreme forest fire."[9] Where harvested biomass is combusted for energy, rather than processed into wood products, short-term emissions are necessarily far greater, and long-term sequestration in forest products is eliminated altogether.

Thinning and post-fire salvage operations reduce the future carbon sequestration potential of a given forest stand by removing trees that otherwise would have continued to draw CO_2 from the atmosphere.[10] This is true even for projects that are intended to reduce fuel loads in order to lessen the potential severity of future wildfires. One recent study concluded that "fuel removal almost always reduces C storage more than the additional C that a stand is able to store when made more resistant to wildfire. . . . [I]t is inefficient to remove large amounts of biomass to reduce the fraction by which other

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[7] Tara Hudiburg, et al., *Carbon Dynamics of Oregon and Northern California Forests and Potential Land-Based Carbon Storage*, 19 ECOLOGICAL APPLICATIONS 163, 163 (2009).

[8] *See id.* at 176-77 (discussing carbon storage reductions associated with shorter rotations and emissions caused by logging); *see also* Mark E. Harmon, et al., *Modeling Carbon Stores in Oregon and Washington Forest Products: 1900-1992*, 33 CLIMATIC CHANGE 521 (1996) (concluding that harvesting for sawtimber results in sequestration of only about 60% of carbon previously stored in forest pools).

[9] Mark E. Harmon, et al., *Effects of Partial Harvest on the Carbon Stores in Douglas-fir/Western Hemlock Forests: A Simulation Study*, 12 ECOSYSTEMS 777, 778 (2009).

[10] *See* Brooks M. Depro, et al., *Public Land, Timber Harvests, and Climate Mitigation: Quantifying Carbon Sequestration Potential on U.S. Public Timberlands*, 255 FOREST ECOLOGY & MGMT. 1122 (2008) (concluding that eliminating timber harvest on public lands would increase forest carbon storage capacity by roughly 40-50% over "business as usual").

biomass components are consumed via combustion."[11] Another recent study confirms that significant amounts of carbon remain sequestered in forest pools even following a high-intensity wildfire.[12] Surveys of the world's most carbon-dense forests, including the moist temperate conifer forests of North America, have confirmed that the greatest accumulations of carbon biomass occur in the absence of human land-use disturbance.[13]

Removal of forest biomass also affects long-term carbon storage in forest soils. Thinning and harvesting operations can reduce carbon inputs to soils and stimulate soil respiration, resulting in both reduced soil sequestration and near-term emissions.[14] Some studies have shown that forests remain net sources of carbon emissions for more than a decade after logging operations, primarily due to increased soil respiration.[15] Fuel treatments that change the amount and composition of decomposing forest biomass can influence long-term below-ground carbon storage.[16]

The time between harvest and complete reabsorption of lost carbon by a forest stand can extend into hundreds of years. For example, one recent study concluded that even assuming perfect conversion of biomass to energy and a one-to-one displacement of fossil-fired generation, it still took from 34 to 228 years for western forests to reach carbon neutrality for biomass used directly for energy generation, and between 201 and 459 years if the biomass was converted to biofuels (the ranges depending upon the characteristics of the trees, forests and fire return intervals).[17] Accordingly, because forest biomass utilization is not carbon neutral in the near term, the near-term effects of carbon emissions associated with biomass combustion must be considered.

It is well established as a matter of science and policy that in order to avoid the worst impacts of global warming and climate change, global temperatures must not be allowed to exceed 2°C over pre-industrial levels.[18] Whether we exceed the 2°C threshold depends on the level at which atmospheric CO_2 levels are eventually stabilized. The greater the CO_2 levels, the greater the risk of exceeding this threshold and triggering

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[11] Stephen R. Mitchell, et al., *Forest Fuel Reduction Alters Fire Severity and Long-Term Carbon Storage in Three Pacific Northwest Ecosystems*, 19 ECOLOGICAL APPLICATIONS 643, 652 (2009); *see also* CHAD HANSON, THE MYTH OF "CATASTROPHIC" WILDFIRE: A NEW ECOLOGICAL PARADIGM OF FOREST HEALTH (2010).

[12] Garrett W. Meigs, et al., *Forest Fire Impacts on Carbon Uptake, Storage, and Emission: The Role of Burn Severity in the Eastern Cascades, Oregon*, 12 ECOSYSTEMS 1246 (2009).

[13] *See* Heather Keith, et al., *Re-evaluation of Forest Biomass Carbon Stocks and Lessons from the World's Most Carbon-Dense Forests*, 106 PROC. NAT'L ACADEMY OF SCI. 11,635 (2009).

[14] Robert Jandl, et al., *How Strongly Can Forest Management Influence Soil Carbon Sequestration?*, 137 GEODERMA 253, 257-58 (2007).

[15] *Id.* at 258.

[16] Mitchell 2009 at 652.

[17] Mitchell 2009 at 651.

[18] J. Hansen, et al., *Target Atmospheric CO_2: Where Should Humanity Aim?*, 2 OPEN ATMOS. SCI. J. 217 (2008).

likely catastrophic climate changes. The probability of overshooting 2°C is as follows according to Hare and Meinshausen (2006) [19]:

85% (68-99%) at 550 ppm CO_2 eq (= 475 ppm CO_2)
47% (26-76%) at 450 ppm CO_2 eq (=400 ppm CO_2)
27% (2-57%) at 400 ppm CO_2 eq (= 350 ppm CO_2)
8% (0-31%) at 350 ppm CO_2 eq

According to these scientists, "[o]nly scenarios that aim at stabilization levels at or below 400 ppm CO_2 equivalence (~350 ppm CO_2) can limit the probability of exceeding 2°C to reasonable levels."[20] But in order to achieve stabilization levels that avert the worst impacts of climate change, emissions must peak by about 2015, and must decline very rapidly thereafter.[21]

In short, minimizing CO_2 emissions in the *next few years* is critically important to meeting climate targets, even if some of all of that CO_2 might in theory be reabsorbed from the atmosphere in the decades or centuries to come. The science makes clear that the time frame for resequestration of CO_2 emitted from forest biomass combustion is on the order of decades or centuries, not years. Indeed, in evaluating carbon emissions from other biofuels, independent scientists have begun to develop strategies for evaluating the carbon impacts of biofuels in relation to the high social and environmental cost of short-term emissions.[22] Even EPA has begun to recognize the importance of this temporal analysis in other contexts.[23] Short-term CO_2 emissions from woody biomass combustion are thus *significant*—not "neutral"—in the context of efforts to avoid the worst impacts of climate change, and should be treated as such in both environmental analysis and air permitting decisions. EPA's failure to acknowledge this fact in the context of the annual emissions inventory is arbitrary and unsupportable.

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[19] B. Hare & M. Meinshausen, *How Much Warming Are We Committed To and How Much Can Be Avoided?*, 75 CLIMATIC CHANGE 111 (2006).
[20] *Id.* at 137.
[21] *See* IAN ALLISON, ET AL., THE COPENHAGEN DIAGNOSIS: UPDATING THE WORLD ON THE LATEST CLIMATE SCIENCE 9 (2009); *see also* M. den Elzen & N. Höhne, *Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets*, 91 CLIMATIC CHANGE 249 (2008).
[22] *See* M. O'Hare et al., *Proper Accounting for Time Increases Crop-Based Biofuels' Greenhouse Gas Deficit Versus Petroleum*, 4 ENVTL. RESEARCH LETT. 024001 (2009) (applying discount rate to account for importance of early emissions).
[23] *See* U.S. EPA, *EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels* (2009) ("[T]he time horizon over which emissions are analyzed and the application of a discount rate to value near-term versus longer-term emissions are critical factors").

III. Logging for Biomass Combustion Is Potentially More Harmful to the Climate and the Forest than Natural Fire.

Although EPA does not specifically mention it, another common justification for treating forest biomass as "carbon neutral" is that if not removed and burned for energy, wood is likely to burn up in forest fires, resulting in both uncontrolled carbon emissions and substantial ecological damage. Once again, recent scientific analysis has shown this premise to be false in terms of both carbon accounting and forest ecology.

Combustion of trees, brush, and litter in forest fires releases carbon emissions. Yet the emissions from fires may be far lower (and far fewer live trees may be killed) than previously believed, depending upon forest type and fire intensity.[24] Carbon lost in fires also may rapidly be resequestered by early successional species following disturbance.[25] Furthermore, recent scientific studies call into question the entire enterprise of removing (and burning) biomass in order to avoid carbon emissions associated with wildfire:

> [F]uel removal almost always reduces C storage more than the additional C that a stand is able to store when made more resistant to wildfire. Leaves and leaf litter can and do have the majority of their biomass consumed in a high-severity wildfire, but most of the C stored in forest biomass (stem wood, branches, coarse woody debris) remains unconsumed even by high-severity wildfires. For this reason, it is inefficient to remove large amounts of biomass to reduce the fraction by which other biomass components are consumed via combustion.[26]

Accordingly, it is not accurate to assume that carbon emissions from biomass combustion would have occurred in the forest anyway, on the same time scales and to the same degree, as a result of fire. Indeed, biomass energy generation ensures that forest biomass is converted into carbon dioxide on a very short time scale, whether or not similar emissions would have occurred as a result of fire, and regardless of whether logging is as effective as natural succession in facilitating sequestration of those emissions. Once again, these detailed questions must be answered before any particular biomass energy project can claim to be "carbon-neutral."

Current scientific work also indicates that fire, even the high-intensity variety, is a natural event that we should accept and encourage, not attempt to forestall through speculative, intensive, and destructive logging projects aimed at "forest cleaning" or "fuel reduction."[27] The dead trees left standing after a high-intensity fire provide critical wildlife habitat as well as soil nutrients that encourage rapid growth of early successional species. Moreover, unlike emissions produced in biomass energy facilities, carbon in standing dead trees and forest floor pools remains sequestered for a long time following

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[24] *See, e.g.*, Meigs 2009.

[25] *See id.* at 1260-61.

[26] Mitchell 2009 at 652.

[27] *See generally* Hanson 2010.

even a high-intensity fire, and decays slowly into the atmosphere even as new plant growth recolonizes a burned area. The eventuality of forest fire cannot be used as an excuse for wholesale logging and burning of forests to create energy.

Finally, the demand for wood created by large-scale construction of biomass energy facilities is likely to be more than our forests can sustain, and thus may have very significant cumulative impacts on biodiversity, water quality, and forest health.[28] In addition, if each of these facilities were to claim "carbon neutrality," in the absence of any evidence or analysis, the result could be a dramatic and uncontrolled overall increase in near-term CO_2 emissions during precisely the time period when emissions most need to be curtailed.

IV. Conclusion

The "carbon neutrality" assumption is just that—an assumption, not a fact. "Carbon neutrality," if it exists at all, must be demonstrated on a project-specific basis, taking into account all emissions from biomass production, transport, processing, and combustion, all emissions and lost sequestration capacity associated with forest thinning and clearing operations, and actual analysis of fossil fuel displacement. In the absence of such a demonstration, the actual emissions from biomass combustion must be counted in EPA's annual emissions inventory. EPA must revise the Inventory to eliminate reliance on the "carbon neutrality" myth, and must replace it with an accurate and comprehensive accounting methodology for biomass emissions.

Thank you for your consideration of our comments. Please feel free to contact Kevin Bundy at (415) 462-9683 x313 with any questions.

Sincerely,

Kevin P. Bundy
Senior Attorney
Center for Biological Diversity

Margaret E. Sheehan, Esq.
Director
The Biomass Accountability Project, Inc.

Mike Ewall
Founder and Director
Energy Justice Network

Ananda Lee Tan
North American Program Coordinator
Global Alliance for Incinerator Alternatives

Eleanor Tillinghast
President
Green Berkshires, Inc.

Chris Matera
Founder
Massachusetts Forest Watch

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[28] *See, e.g.*, V.A. Sample, *Summary/synthesis: What Role Will Forests Play in America's Long-Term Energy Future?* (2009) at 16-17.

References Cited

Ian Allison, et al., *The Copenhagen Diagnosis, 2009: Updating the world on the Latest Climate Science* (2009).

Brooks M. Depro, et al., *Public Land, Timber Harvests, and Climate Mitigation: Quantifying Carbon Sequestration Potential on U.S. Public Timberlands*, 255 FOREST ECOLOGY & MGMT. 1122 (2008).

M. den Elzen & N. Höhne, *Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets*, 91 CLIMATIC CHANGE 249 (2008).

James Hansen, et al., *Target Atmospheric* CO_2*: Where Should Humanity Aim?*, 2 OPEN ATMOS. SCI. J. 217 (2008).

Chad Hanson, *The Myth of "Catastrophic" Wildfire: A New Ecological Paradigm of Forest Health* (2010).

B. Hare & M. Meinshausen, *How Much Warming Are We Committed To and How Much Can Be Avoided?*, 75 CLIMATIC CHANGE 111 (2006).

Mark E. Harmon, et al., *Effects of Partial Harvest on the Carbon Stores in Douglas-fir/Western Hemlock Forests: A Simulation Study*, 12 ECOSYSTEMS 777, 778 (2009).

Mark E. Harmon, et al., *Modeling Carbon Stores in Oregon and Washington Forest Products: 1900-1992*, 33 CLIMATIC CHANGE 521 (1996).

Tara Hudiburg, et al., *Carbon Dynamics of Oregon and Northern California Forests and Potential Land-Based Carbon Storage*, 19 ECOLOGICAL APPLICATIONS 163, 163 (2009).

Robert Jandl, et al., *How Strongly Can Forest Management Influence Soil Carbon Sequestration?*, 137 GEODERMA 253, 257-58 (2007).

Heather Keith, et al., *Re-evaluation of Forest Biomass Carbon Stocks and Lessons from the World's Most Carbon-Dense Forests*, 106 PROC. NAT'L ACADEMY OF SCI. 11,635 (2009).

Garrett W. Meigs, et al., *Forest Fire Impacts on Carbon Uptake, Storage, and Emission: The Role of Burn Severity in the Eastern Cascades, Oregon*, 12 ECOSYSTEMS 1246 (2009).

Stephen R. Mitchell, et al., *Forest Fuel Reduction Alters Fire Severity and Long-Term Carbon Storage in Three Pacific Northwest Ecosystems*, 19 ECOLOGICAL APPLICATIONS 643, 652 (2009).

M. O'Hare et al., *Proper Accounting for Time Increases Crop-Based Biofuels' Greenhouse Gas Deficit Versus Petroleum*, 4 ENVTL. RESEARCH LETT. 024001 (2009).

V.A. Sample, *Summary/synthesis: What Role Will Forests Play in America's Long-Term Energy Future?* (2009).

Timothy Searchinger, et al., *Fixing a Critical Climate Accounting Error*, 326 SCIENCE 527 (2009).

U.S. EPA, *EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels* (2009).

Appendix E

NACWA
A Clear Commitment to America's Waters

April 14, 2010

Leif Hockstad
U.S. Environmental Protection Agency
Climate Change Division (6207J)
1200 Pennsylvania Ave, NW
Washington, DC 20460
Via Email: Hockstad.Leif@epa.gov

Re: NACWA Comments on Wastewater Treatment Emissions Estimates in EPA's Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*

Dear Mr. Hockstad:

The National Association of Clean Water Agencies (NACWA) has reviewed Section 8.2, *Wastewater Treatment*, of the U.S. Environmental Protection Agency's (EPA) draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008* (*Draft Inventory*) and offers the following comments and technical information. NACWA represents the interests of nearly 300 publicly owned wastewater treatment agencies nationwide, serving the majority of the sewered population in the U.S. NACWA members are very much aware of the growing importance of global climate change and are already engaged in efforts to reduce greenhouse gas (GHG) emissions. The wastewater treatment category of the *Inventory* consistently ranks in the top categories for nitrous oxide and methane emissions in the U.S., although the emissions are much smaller in magnitude than for the highest ranked categories. The wastewater category is broad, including publicly owned treatment works (POTWs), septic systems, and industrial wastewater treatment systems. Our review focused on the portion of the wastewater treatment emissions from POTWs, which are a fraction of the total wastewater treatment emissions.

NACWA submitted comments on the three previous *Inventories*, and we appreciate EPA's response to these comments and the Agency's willingness to work with NACWA to refine the GHG emissions estimates for POTWs. Some adjustments have been made in past years to the methods used to calculate GHG emissions from POTWs, and NACWA has supported these changes. No significant changes were made between the 2007 and 2008 *Inventories*, however, and NACWA believes that the *Inventory* emission calculation methods could still be improved to more accurately reflect actual emissions from POTWs.

In the past, the *Inventory* has been used only for information purposes, not for regulation. However, in EPA's proposed *Prevention of Significant Deterioration and Title V GHG Tailoring Rule* ("Proposed Tailoring Rule"), the methods for calculating GHG emissions in the *Inventory* were cited as the methods that a facility must use to calculate whether the threshold for regulation of GHG emissions under the Clean Air Act (CAA) is exceeded. If EPA plans to use the *Inventory* in its regulations, then it is especially important that the *Inventory* calculation methods accurately reflect actual emissions from facilities. However, the *Inventory* calculation methods may not be the best tool for regulatory compliance. As NACWA pointed out in its comments to EPA on the Proposed Tailoring Rule, the *Inventory* is meant to provide a nationwide estimate of emissions from broad categories of facilities, not emissions from individual facilities. In addition, the methods used to calculate emissions in the *Inventory* for POTWs differ from the methods that POTWs must use to calculate their emissions under the *Mandatory Reporting of Greenhouse Gases Rule*. NACWA believes that the Agency must determine one calculation method to be used in all of its GHG-related regulations, rather than requiring facilities such as POTWs to use different calculations for different regulations.

In the comments below, NACWA presents recommendations for changes that should be made to the *Draft Inventory* to improve its estimates of emissions from centralized treatment facilities. NACWA recommends that whenever possible, the domestic sources of emission should be broken down into septic system and centralized treatment sources. For the nitrous oxide emissions estimates, NACWA urges EPA to consider published literature values of nitrogen loading rates to POTWs, and to collect its own data if necessary to verify these rates. In addition, several changes need to be made to the equations used to calculate nitrous oxide emissions to fix typographical errors and to make the values calculated by EPA reproducible.

Wastewater Treatment Emissions Summary

Tables 8-6 and 8-7 in the *Draft Inventory* provide a summary of methane and nitrous oxide emissions, showing total emissions as well as the separate contributions from domestic and industrial wastewater treatment. NACWA recommends that the domestic emissions be broken down into emissions from septic systems and from centralized systems. In Table 8-9, the methane emissions from industrial sources are broken down according to each industrial sector, but no similar division is shown for domestic sources. Septic systems contribute most of the methane emissions from domestic sources, while centralized systems are shown to be responsible for all of the nitrous oxide emissions. Given these significant differences, dividing domestic emissions between septic and centralized systems would more clearly illustrate and summarize the emission sources.

Domestic Wastewater Nitrous Oxide Emission Estimates

The *Draft Inventory* calculates nitrous oxide emissions from POTWs using estimated nitrogen loadings to wastewater that are based on reported annual protein consumption. This is the methodology used in the Intergovernmental Panel on Climate Change (IPCC) protocol document[1] (*IPCC Guidelines*). Expressed as nitrogen (N), the estimated nitrogen loading rate to POTWs for domestic sources is:

(32.4 kg consumed protein/capita-year) x (0.16 kg N/kg protein) x (1.4 factor for non-consumed protein)
= 7.26 kg N/capita-year

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[1] IPCC, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Prepared by the National 18 Greenhouse Gas Inventories Programme, Eggleston H.S., Buenida L., Miwa K., Ngara T., and Tanabe K. (eds.) 19 Published: IGES, Japan, 2006.

Changing the units of this value to grams of nitrogen on a daily basis results in:

$$(7.26 \text{ kg N/capita-year}) \times (1000 \text{ g/kg}) \times (1 \text{ year}/365 \text{ days})$$
$$= 19.9 \text{ g N/capita-day}$$

The nitrogen loading rate is further increased by a factor of 1.25 to account for industrial and commercial contributions, as follows:

$$1.25 \times (19.75 \text{ g N/capita-year})$$
$$= 24.9 \text{ g N/capita-day}$$

Comparison of EPA's Estimated Nitrogen Loading Rates to Published and Surveyed Rates

NACWA believes that both of the above loading rates are too high, and that EPA needs to conduct more research to determine more accurate loading rates to use in the *Inventory*. As NACWA has pointed out in its previous comments on the *Inventory*, the rates currently used in the *Draft Inventory* are higher than rates presented in standard references such as Metcalf & Eddy[2]. Metcalf & Eddy report per capita nitrogen loading rates to wastewater of 15 g N/capita-day, a value usually considered the "industry standard" by POTWs. These values are supported by a wealth of data and have been widely confirmed in U.S. practice. The type of data used in Metcalf & Eddy represents all domestic sources of nitrogen, including meal production and consumption, the use of other nitrogen containing compounds, and both residential and commercial sources.

In NACWA's comments on the *Draft Inventory* for 1990-2007, we presented the results of a literature review to find other nitrogen loading rates. In addition, NACWA conducted a survey of measured total nitrogen loading rates for 48 wastewater treatment facilities throughout the U.S., with a total service population of over 17 million people. Since these data are from measurements of nitrogen loading to the POTW, the nitrogen loading rate includes all sources (residential, commercial, and industrial) for the service communities represented. All of the nitrogen loading rate values are summarized in Table 1. The literature review results and table of survey data are included again for your reference in Attachments A and B, respectively.

Table 1. Summary of nitrogen loading values to POTWs.

Reference	Nitrogen Loading Rate (g N/capita-day)
EPA *Draft Inventory* – Domestic Sources	19.9
EPA *Draft Inventory* – Domestic, Industrial, and Commercial Sources	24.9
Metcalf & Eddy – "Industry Standard"	15
Literature Review – Range of Reported Values	6-22.7
Literature Review – Average of Reported Values	13.3
NACWA Data	15.1

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[2] Tchobanoglous, G., F.L. Burton, and H.D. Stensel, *Wastewater Engineering: Treatment and Reuse, Metcalf & Eddy, Inc.* 4th Edition, McGraw-Hill, New York, 2003.

The nitrogen loading values found in the literature review average 13.3 g N/capita-day, which is even less than the value 15 g N/capita-day reported by Metcalf & Eddy. The average nitrogen loading value found in the NACWA survey of POTWs was 15.1 g N/capita-day, which agrees almost exactly with the Metcalf & Eddy value. The value used in the *Draft Inventory* of 19.9 g N/capita-day for domestic sources only falls within the upper part of two ranges found in the literature review, while the derived value of 24.9 g N/capita-day for all sources is above all of the published values and is also above the highest value found in the NACWA survey of POTWs. EPA's own references cite values of 11.2, 12, 6-17, and 8.16-22.7 g N/capita-day, which are all lower than the nitrogen loading rate for all sources used in the *Draft Inventory*. NACWA believes that the value used in the *Inventory* should be closer to the average nitrogen loading value from the available literature, rather than in the very upper part of a range of values.

If the *Inventory* methodology is used to convert only the per capita protein consumption into per capita nitrogen loading, without the additional factors to account for non-consumed protein and non-domestic sources, the result is:

$$(32.2 \text{ kg protein/capita-year}) \times (0.16 \text{ kg N/kg Protein}) \times (1{,}000 \text{ g/kg}) \div (365.25 \text{ days/yr})$$
$$= 14.1 \text{ g N/capita-day}$$

This value is extremely close to the value found in the NACWA data and to the average value from the literature survey. EPA makes two assumptions to convert this value of protein consumption (expressed as N) into the nitrogen contribution from domestic sources:

1. All of the protein consumed is excreted; and
2. The protein consumed is multiplied by the 1.4 factor for non-consumed protein to represent other sources of nitrogen in domestic wastewater.

The first assumption, that all protein consumed is excreted, is not clearly stated in the *Draft Inventory*, but it appears to be made based on the equations and values reported. EPA should clarify whether or not this assumption is made. If the assumption is not made, then the fraction of consumed protein that is excreted should be reported in the *Inventory*.

The result of these two assumptions translates into a loading rate of 19.9 g N/capita-day from domestic sources. While protein consumption may be a reasonable "starting point" for the estimation of per capita nitrogen loading, the factors used to convert per capita protein consumption to per capita nitrogen loading may be overly conservative. The actual per capita POTW influent total nitrogen value may instead be:

1. A fraction of the reported per capita protein consumption (expressed as N), due to less protein being excreted than is consumed, with some additional nitrogen from non-consumed protein;
2. Accurately predicted by the per capita protein consumption and the factor of 1.4 is too high for the addition of non-consumed protein to the wastewater; or
3. A combination of the two scenarios above.

Modifying the nitrogen loading rates used in the *Draft Inventory* to account for these scenarios may result in more agreement between the calculated rates and the rates cited in the literature and verified with the NACWA survey.

Recommendations for Modifying EPA's Estimation Methodology

While it may be reasonable to use per capita protein consumption as an index of potential changes in POTW influent per capita nitrogen values over the years, the factors used to convert per capita protein consumption data into per capita POTW influent nitrogen values should be adjusted to reflect real-world data. EPA has agreed in the current *Draft Inventory* that "obtaining data on the changes in average influent N concentrations to centralized treatment systems over the time series would improve the estimate of total N entering the system, which would reduce or eliminate the need for other factors for non-consumed protein or industrial flow." NACWA urges EPA to work to obtain the appropriate data to justify changes to the *Inventory*, either to adjust the factors applied to convert protein consumption to influent nitrogen values, or to change the calculation to a purely data-based approach.

EPA noted in the current *Draft Inventory* that "the dataset previously provided by NACWA was reviewed to determine if it was representative of the larger population of centralized treatment plants for potential inclusion into the inventory." However, EPA concluded that "this limited dataset did not represent the number of systems by state and the service populations served in the United States." NACWA disagrees with this conclusion. The literature review documented peer-reviewed nitrogen loading values that are widely used and accepted by the wastewater sector. NACWA conducted the survey of measured nitrogen loading rates at POTWs to determine if the values published in the literature continue to be appropriate. The agreement between the measured values and the literature shows that the literature values are valid. NACWA believes that the literature – including EPA's own publications – provides sufficient information to allow changes to be made to the *Inventory* emissions calculations methods.

If EPA judges the peer-reviewed literature values to be insufficient proof for changing the *Inventory*, NACWA suggests that the information submitted provides EPA with a strong argument to conduct its own study of nitrogen loading rates to centralized treatment plants. EPA should have enough data available through its National Pollution Discharge Elimination System (NPDES) permitting program to determine an appropriate and justifiable nitrogen loading rate. The NPDES permitting program is nation-wide in scope and long-term in its nature, which would allow changes to be made in emissions estimates over the time series represented in the *Inventory*. Since EPA believes that further data of a broader and more representative scope are required before changing the *Inventory*, the NPDES database would certainly suffice as it represents every central POTW in the U.S. We urge EPA to conduct this analysis if it believes that further evaluation is needed to justify the standard, well-accepted nitrogen loading values documented in the literature.

NACWA believes that using the literature nitrogen loading values or EPA-collected values from U.S. POTWs would better reflect the actual emissions from POTWs in the U.S. than the current methods based on the *IPCC Guidelines*. The *IPCC Guidelines* do not necessarily reflect actual conditions at POTWs throughout the U.S. This is illustrated by the emission factor ("EF_1") of 3.2 g N_2O/person-year for plants with no intentional denitrification, used in the *Draft Inventory* and in the *IPCC Guidelines* to calculate nitrous oxide emissions from centralized wastewater treatment plants. This value was obtained from a single study of a very small wastewater treatment plant (1.06 million gallons per day, or MGD) in a small university town in New Hampshire. The population of this town is 12,500 during the school year, but drops to 6,200 in the summer months, during which most of the measurements for this study were made. If the IPCC can use this single study to define an emission factor that is used for centralized treatment facilities all over the world, certainly EPA can justify changing the nitrogen loading rate for facilities in the U.S. based on multiple literature values and data that it can collect from POTWs across the nation.

Recommendations for Revisions to the Emissions Equations

NACWA recommends that several changes be made to the equations on page 8-13 used to calculate the nitrous oxide emissions from domestic wastewater and to the definitions of the factors used in these equations on page 8-14:

1. In the $N_2O_{WOUT\ NIT/DENIT}$ equation (line 44, page 8-13), the $F_{IND\text{-}COM}$ factor should be moved outside of the square brackets. This is a typographical error rather than an error that affects the calculations.
2. In the $N_2O_{EFFLUENT}$ equation (line 45, page 8-13), the US_{POP} factor should be multiplied by the WWTP factor, as it is in the $N_2O_{WOUT\ NIT/DENIT}$ equation, since septic system users should not be included in the amount of effluent discharged to aquatic environments. NACWA recommends that any nitrous oxide contributions from septic systems be calculated in a separate equation if they are even included in the *Inventory*.
3. The units provided in the definitions of N_2O_{TOTAL}, N_2O_{PLANT}, $N_2O_{NIT/DENIT}$, and $N_2O_{WOUT\ NIT/DENIT}$ (lines 2-7, page 8-14) should be Gg, not kg, since conversions are made to Gg in the equations used to calculate these values.
4. The value of 269 Tg N for N_{SLUDGE} (line 37, page 8-14) appears to be an error, resulting in a negative value for $N_2O_{EFFLUENT}$. The value of 141 Gg N found in the Annex in Table A-193 (page A-231) is a more appropriate magnitude. However, even substituting this 141 Gg N value for N_{SLUDGE} does not result in a N_{TOTAL} value that agrees with the value of 15.9 Gg N_2O in Table 8-7. EPA should review the equation for $N_2O_{EFFLUENT}$ and all of the values used in it for accuracy.

Thank you for consideration of our comments on the *Draft Inventory*. Please contact me at 202/296-9836 or *cfinley@nacwa.org* if you have any questions about NACWA's comments.

Sincerely,

Cynthia A. Finley

Cynthia A. Finley
Director, Regulatory Affairs

Attachments

Attachment A

References in literature for nitrogen per capita loading rates.

Reference	Value (g N/ capita-day)	Comments
U.S. EPA, *Manual: Nitrogen Control*, EPA/625/R-93/010 Office of Research and Development, Office of Water, Washington DC 20460, September 1993.	12	Residential contribution.
U.S. EPA, *Manual: Nitrogen Control*, EPA/625/R-93/010 Office of Research and Development, Office of Water, Washington DC 20460, September 1993.	8.16-22.7	Based on raw influent wastewater characteristics of per capita pollutant generation rates of 0.18-0.25 lb/capita/day (BOD). The pollutant relationship between BOD and TKN was defined as 0.1-0.2 TKN/BOD. (Table 2-2, p. 26)
U.S. EPA, *Systems Manual: Onsite Wastewater Treatment*, EPA/625/R-00/008 Office of Research and Development, Office of Water, Washington DC 20460, February 2002.	6-17	Total nitrogen loading value from Table 3-7, Constituent Mass Loadings and Concentrations in Typical Residential Wastewater. This applies to typical residential households with standard water-using fixtures and appliances.
U.S. EPA, *Systems Manual: Onsite Wastewater Treatment*, EPA/625/R-00/008 Office of Research and Development, Office of Water, Washington DC 20460, February 2002.	11.2	Total nitrogen loading value contributions by source in Table 3-8. Estimates 0.6 g/person/day from the garbage disposal, 8.7 g from toilets, and 1.9 g from bathing, sinks, and appliances for the total of 11.2 g/person/day of nitrogen.
Metcalf & Eddy, Inc., *Wastewater Engineering: Treatment, Disposal, Reuse*, 2nd Edition, McGraw-Hill Book Company, NY, 1979.	15	"Normal domestic wastewater." Range of 10-18 g N/capita-day, with complete grinding of food waste.
Metcalf & Eddy, Inc., *Wastewater Engineering: Treatment, Disposal, Reuse*, 3rd Edition, McGraw-Hill Book Company, NY, 1991.	12	"Normal domestic wastewater" without contribution from ground kitchen waste. Range of 9 to 14 g N/capita-day.
Metcalf & Eddy, Inc., *Wastewater Engineering: Treatment, Disposal, Reuse*, 4th Edition, McGraw-Hill Book Company, NY, 2003.	9-22	Value for the United States was obtained from Table 3-14, p. 184 of typical wastewater constituent data for various countries.

Henze, M. and A. Ledin, "Types, Characteristics and Quantities of Classic, Combined Domestic Wastewaters," in *Decentralized Sanitation and Reuse: Concepts, Systems and Implementation*, Lens, P., G. Zeeman, and G. Lettinga Ed, IWA Publishing, London, 2001.	14	Values for Denmark and USA reported to be similar to range from 14 to 19 g N/capita-day.
Matsui, S., M. Henze, G. Ho, and R. Otterpohl, "Emerging Paradigms in Water Supply and Sanitation," in *Frontiers in Urban Water Management: Deadlock or Hope*, Maksimović, C and J. A. Tejada-Guibet Ed., IWA Publishing, 2001.	13	Household wastewater.
Average Value	**13.3**	
Low Value	**6**	
High Value	**22.7**	

Attachment B

Nitrogen loading data from wastewater treatment facilities in the U.S. (The names, cities, and other information about the treatment facilities are not included in this table, but this information can be provided by NACWA if needed.)

State	**Service Population (End of Data Period)**	**Nitrogen Loading (g/person-day)**	**Period of Data Record**
CA	95,000	15.2	1995-2000
CA	80,000	11.0	1995
CA	102,000	16.6	1985-1986
CA	25,800	13.3	1993
CA	200,000	14.4	1988
CA	60,000	16.3	1994
CA	360,000	9.1	1983
CA	35,900	11.4	1995
CA	965,185	15.0	2007
CA	1,337,912	17.0	2007
CA	127,658	13.0	2006
CA	156,759	17.0	2006
CT	18,585	16.8	1998-2005
CT	5,400	20	
CT	12,980	14.1	1999-2001
CT	17,650	16.8	
CT	49,815	13.2	2002-2003
FL	187,320	15.6	1990-1999
IA	-	19.07	
IL	67,500	10.6	1999
MA	2,060,000	15	1986-1987
MA	89,589	15.4	2000
MA	6,986	11.8	2001-2006
MA	9,000	14.1	1997-2000
MN	52,150	7.0	1998
MT	139,200	14.53	2000-2005

MT	31,700	10.44	2003
MT	33,000	9.99	2004
MT	35,700	11.80	2005
NC	800,000	14.53	2007
NE	3,350	16.80	Dec. 2007
NH	17,000	20.0	2005
NJ	192,089	15.9	1999-2001
NM	-	16.8	2002-present
NV	600,000	16.80	2007
NY	26,622	22.7	1997-1999
NY	26,000	16.5	Jan. 2004- July 2007
OR	2000	19.5	2000-2004
OR	2000	15.9	1994-2000
OR	60,000	20.43	2005-2006
PA	900,000	9.7	2005
RI	139,000	19.1	1997-1998
TX	875,355	13.2	1996-2005
VA	300,818	15.9	2007
VA	273,356	15.9	July 2005 – June 2006
VA	361,582	14.5	FY 1990-2007
VA	115,000	19.1	2004-2006
VA	412,700	11.53	2001-2003
VA	82,000	18.16	2003-2006
WA	96,500	16.3	April-Oct. 2007
Average Value		**15.1**	
Low Value		**9.1**	
High Value		**22.7**	

Appendix F

Lifetime-leveraging

An approach to achieving international agreement and effective climate protection using mitigation of short-lived greenhouse gases

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Received 29 August 2008
Revised 5 September 2008
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Abstract

Purpose – The purpose of this paper is to suggest an approach to post-Kyoto climate negotiations that could provide a way out of the apparent deadlock between developed and developing countries. This is an urgent issue as the world already appears to be close to a level of climate change that could be considered "dangerous".

Design/methodology/approach – The paper explores the potential that control of short-lived greenhouse gases such as methane, tropospheric ozone, and soot could have, in addition to steep cutbacks in industrialized nations, to both mitigate global warming and overcome political stalemate in the international climate negotiations.

Findings – Although rarely mentioned in climate discourse, reducing emissions of short-lived greenhouse gases offers a cost-effective way of actually reducing the radiative forcing in the atmosphere, while at the same time producing substantial subsidiary benefits such as improved urban air quality. The paper suggests leveraging this potential in the post-Kyoto treaty in order to "buy time" to address the arguably more difficult problem of essentially eliminating fossil-fuel related CO_2 emissions, which will ultimately be required to truly bring climate change under control. While high-income countries work on steep cutbacks of all greenhouse gas emissions, middle-income nations could make significant additional contributions by undertaking commitments to control only short-lived greenhouse gases until they reached a threshold level of per-capita GDP, at which point they would cap and begin reducing all greenhouse gas emissions.

Originality/value – This paper recognizes that political tradeoffs will have to be made in negotiating the next climate treaty, and offers a way of approaching these tradeoffs that could minimize resulting environmental damage.

Keywords Climatology, Global warming, International cooperation, Environmental politics

Paper type Research paper

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Introduction

The UN Framework Convention on Climate Change (UNFCCC), negotiated in 1992, sets as its objective the stabilization of greenhouse gas concentrations at a level that would avoid "dangerous anthropogenic interference with the climate" (Article 2). The Kyoto Protocol, negotiated under the auspices of the UNFCCC, expires in 2012 and is widely regarded as a necessary but incomplete first step on the path toward achieving this objective. It put in place an international cap-and-trade framework that can be built on in future negotiations, but it restricted the emissions of relatively few countries and did not set long-term emissions targets. Global emissions have risen 23 per cent since the treaty was negotiated in 1997 (Marland *et al.*, 2007; BP, 2007).

Coincident with the accelerating rise in emissions and global temperature over the past decade have been scientific studies of the impacts on vegetation, wildlife, and the world's glaciers and ice sheets to climate change. These indicate that even relatively small increases in the global average temperature can lead to significant changes in the climate (Intergovernmental Panel on Climate Change – IPCC, 2007a), and it seems increasingly clear that impacts on society are likely to be more immediate and serious than previously indicated (IPCC, 2007b). As a result, it is now reasonably clear that global emissions need to peak and begin declining no later than 2020 to give a reasonable probability of avoiding the most serious climatic consequences (Meinshausen, 2006). The successor agreement to the Kyoto Protocol will therefore be critical in determining whether the world will avoid a dangerous level of climatic change.

The post-Kyoto treaty must possess two key characteristics: it must be stringent enough to avoid dangerous climate change and it must be structured in a way that provides incentives for participation of the world's major emitters. It is unclear which of these requirements will be the most difficult to achieve. Increasing scientific evidence of positive feedback mechanisms and of the Earth's sensitivity to past climatic changes has suggested that dangerous and irreversible climate change can be expected at a warming between 2 and 2.5°C above pre-industrial temperatures[1]. The atmosphere already contains enough long-lived greenhouse gases to raise global temperature by over 2°C[2]. Of that, 0.8°C of warming has already been realized, 0.6°C will be realized as the climate system comes to equilibrium, and the remainder is being offset by the cooling effect of (relatively short-lived) sulfate aerosols (IPCC, 2007a). Clearly, the Earth is already flirting with a dangerous level of climate change and steep and deep emissions cuts will be necessary if the threshold is to be avoided.

Despite the urgency of the threat, summoning the international political will to agree and enforce these strict limits could prove even more difficult than making the cuts themselves. The USA, the world's largest emitter over the twentieth century, has declined to ratify the Kyoto Protocol on the basis that it does not restrict emissions from developing countries that are also big emitters. Conversely, these developing countries, particularly China and India, have given little indication that they would accept any limit to their CO_2 emissions. Russia, the world's third largest emitter, recently announced that it would not undertake any future limits to emissions under a post-Kyoto agreement.

In this difficult political environment, it is inevitable that compromises will have to be made. Creative approaches to crafting the new international agreement will ensure that necessary political tradeoffs are made in a manner that minimizes damage to the environmental effectiveness of the agreement. The following sections describe the current deadlock in the negotiations process and the part that short-lived greenhouse gases play in the global warming problem. Then an approach is outlined through which mitigation of these short-lived gases could be incorporated into a future agreement and the equity, cost-effectiveness, and climatic effectiveness of such an agreement are examined in turn.

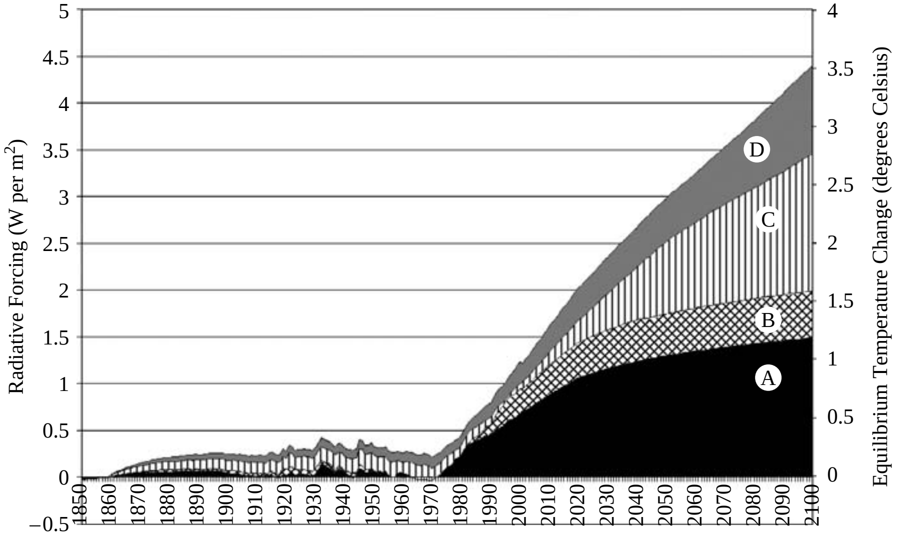
The first mover problem and the current climate impasse

All discussions of international climate agreements raise ethical issues regarding responsibility for past and future warming and the equity of the cost distribution of proposed solutions. As shown in Figure 1, the pattern of regional contributions to global warming over time shows that accumulated emissions from the OECD and former Soviet Union, with 20 per cent of the world's population, currently account for roughly 75 per cent of the warming problem. Per-capita emissions show an even greater disparity, with an American's carbon footprint currently five times the global average and 200 times that of someone living in one of the poorest countries. Indeed, the UN estimates that the average air conditioning unit in Florida is responsible for more CO_2 in a year than a Cambodian is in a lifetime, and that use of an average dishwasher in Europe results in emission of as much CO_2 in a year as three Ethiopians (UNDP, 2007).

These huge differences in per-capita emissions are significant because they are a product of economic development in high-income countries that has been powered by use of inexpensive fossil fuels. Developing countries ask why, when global warming ranks relatively low on a long list of humanitarian and economic priorities, and when greenhouse gas emissions are today closely correlated with the energy consumption that drives economic growth and welfare improvement, they should not do the same.

However, Figure 1 shows that even under a relatively modest emissions growth scenario, non-OECD countries will account for about 70 per cent of the climate forcing in 2100, and an even larger part of the growth in emissions over the next 100 years. Over the twenty-first century, with no internationally-agreed constraint, the developing countries will emit four to five times the amount of carbon dioxide emitted by the developed economies over the last century and a half. Clearly, even were it politically feasible to do so, high-income nations will be unable to solve the climate change problem alone: even were the OECD countries to completely cease emissions in 2013 after the expiry of the Kyoto Protocol, a "dangerous" level of greenhouse gas concentrations would be reached before 2050.

Much of the recent debate on achieving a stabilization of greenhouse gas concentrations has focused on how emissions reductions should be shared between developed and developing nations, particularly the large, rapidly growing developing countries (Posner and Sunstein, 2008; Baer and Athanasiou, 2007; Sugiyama and Deshun, 2004). Given their high per-capita emissions, greater wealth and greater responsibility for greenhouse gases currently accumulated in the atmosphere, the developed countries clearly bear the ethical burden of moving first to reduce greenhouse gas emissions, as reflected in the provisions of the UNFCCC and the Kyoto Protocol.



Notes: Ⓐ– OECD, Ⓑ– former Soviet Union, Ⓒ– Asia, Ⓓ– Africa, Latin America and the Middle East. The B2 scenario from the 2000 Special Report on Emissions Scenarios (IPCC, 2000) was chosen as a 'baseline' scenario for analysis because it is a mid-range scenario. Recent evidence, however, suggests that since 2000, emissions have grown faster than the high-end A1FI scenario, suggesting that the B2 scenario might be, at best, a lower-bound on future emissions (Canadell *et al.* (2007). Note also that the net radiative forcing is plotted, in which the negative forcing from sulfate aerosols is subtracted from the positive forcing from greenhouse gas emissions, occasionally more than canceling the warming responsibility from some regions. A conversion factor of 0.8°C per Wm^{-2} (about 3˚C for a doubling of CO_2) is used. See endnote 5 for a definition of radiative forcing. Includes effect of carbon dioxide, methane, nitrous oxide and sulfate aerosols. This and subsequent graphs were created using emissions from WRI (2007), Houghton (2003), Ramankutty and Foley (1999), Stern and Kaufman (1998), Olivier and Berdowski (1998) and Smith *et al.* (2004), with projected emissions from IPCC (2000) and lifetime and forcing equations from Hansen (2007), IPCC (2001), and IPCC (1997)

Figure 1.
Responsibility for warming commitment by region for the IPCC B2 scenario

However, reducing emissions in developed nations will require a substantial and expensive restructuring of the energy infrastructure, a program that governments are understandably reluctant to undertake without a meaningful commitment from the big emitters among developing nations that they will join in the effort to keep global warming constrained to some agreed level. To effectively prevent dangerous climate change, the next climate agreement must cover all major emitters and so must effectively broker a compromise between the interests and responsibilities of developed and developing nations.

Greenhouse warming: a multi-gas problem

Adequately addressing climate change will require confronting all aspects of the problem. International attention has so far focused primarily on CO_2 emissions from fossil fuels because CO_2 is the single most important greenhouse gas, one of the longest-lived, and is most closely linked with economic development and so is seen to pose the most intractable problem. Large reserves of fossil carbon (particularly coal), which will likely be used to support future economic development in the absence of emissions caps, mean that a large part of the projected increment in greenhouse warming between 2000 and 2100 results from energy-related CO_2 emissions.

These reasons justify early and strong control of CO_2 emissions, but nevertheless, CO_2 accounts for only around half of the current positive forcing from greenhouse gases[3] (IPCC, 2007a), and at least a fifth of this CO_2 forcing is attributable to land-use change and deforestation rather than fossil fuel burning. Other important greenhouse gases include methane, nitrous oxide, the halocarbons, soot, and tropospheric ozone.

As can be seen from Table I, radiative forcing from anthropogenic emissions of methane amounts to more than half the forcing from CO_2 emissions. Similarly, the warming influence of black carbon (soot) emissions appears to be large, especially if the albedo effect of soot deposition on snow, glaciers and ice is accounted for. Models used by the IPCC estimate warming from soot at $0.44\,\mathrm{Wm}^{-2}$ (IPCC, 2007a), but a more recent review by Ramanathan and Carmichael (2008) that includes observational evidence suggests that it could be as high as $0.9\,\mathrm{Wm}^{-2}$. Tropospheric ozone, a product of the emission of several of the gases in Table I, also has a significant positive influence on radiative forcing. Half of the forcing attributable to CO and volatile organic compound (VOC) emissions, and almost a quarter of the warming from methane emissions comes from the effect these gases have of increasing tropospheric ozone concentration. Under baseline scenarios this effect is likely to persist in coming decades – one study found that changing levels of short-lived, radiatively active particles would likely account for 20 per cent of the globally-averaged warming in 2050 (CCSP, 2008).

Crucially, as indicated in Table I, several of these greenhouse gases (i.e. methane, soot, and tropospheric ozone) have relatively short atmospheric lifetimes. Unlike carbon dioxide, which once in the atmosphere creates a radiative perturbation that will

Table I.
Change in radiative forcing from 1750 to 2005 due to emission of various agents

Agent emitted	Net change in radiative forcing in 2005 due to emissions 1750-2005 (Wm^{-2})	Persistence (lifetime) of perturbation	Primary sources
CO_2	1.56	Centuries-millennia	Fossil fuel burning, deforestation and land use change, cement production
CH_4	0.86	12 years	Landfills, natural gas leakage, agriculture
N_2O	0.14	114 years	Fertilizer use, livestock sector, fossil fuel combustion
CFC/HCFC	0.28	100-1,000 years	Aerosols, cleaning products and refrigerants
CO/VOC (O_3precursors)	0.27	CO – months; VOC – hours; (O_3 – days)	CO – incomplete fossil fuel combustion; VOCs – petroleum production and consumption, solvents
Black carbon	0.44-0.9	One week	Fossil fuel combustion, biomass burning

Note: VOC – volatile organic compounds
Sources: IPCC (2007a, p. 33, 207) and new results from Ramanathan and Carmichael (2008)

persist for centuries, these pollutants are removed far more rapidly. This means that reducing these emissions will have a near-immediate effect on the atmospheric concentration of these gases, and so, by extension, on climate forcing. This characteristic can be utilized in planning a successful climate stabilization strategy.

Figure 2 shows the breakdown, by gas and period of emission, of radiative forcing at various points in the twenty-first under the B2 emissions scenario. The green bars show the forcing effects from gases that have yet to be emitted – in other words, the portion of forcing that can be altered by emission reduction strategies put in place in the near future. Because of its relatively short lifetime, strict control of methane emissions between 2000 and 2050 could, in theory, entirely eliminate the warming effect of this gas. Soot and ozone are not shown in Figure 2, but control of the contributing emissions would result in a similarly rapid decrease in forcing. Carbon dioxide, on the other hand has a far longer atmospheric lifetime, so a similar degree of control would result in a reduction in radiative forcing of only 38 per cent by 2050.

Problematically, reducing emissions of CO_2 today will only slow or halt the rate of increase in concentration over the next few decades and so offers little opportunity to actually reduce the amount of committed warming. Since the world already has a level of greenhouse gas concentrations that take it perilously close to the 2-2.5°C threshold likely to lead to dangerous climate change, and in that the world community shows little sign of reining in the growth in fossil fuel emissions, concentrating some near-term attention specifically on the short-lived pollutants can provide a valuable climatic "breathing space" while nations work to develop and deploy technologies that will bring fossil-fuel CO_2 emissions to near zero, as must happen over the next century if climate is to be stabilized.

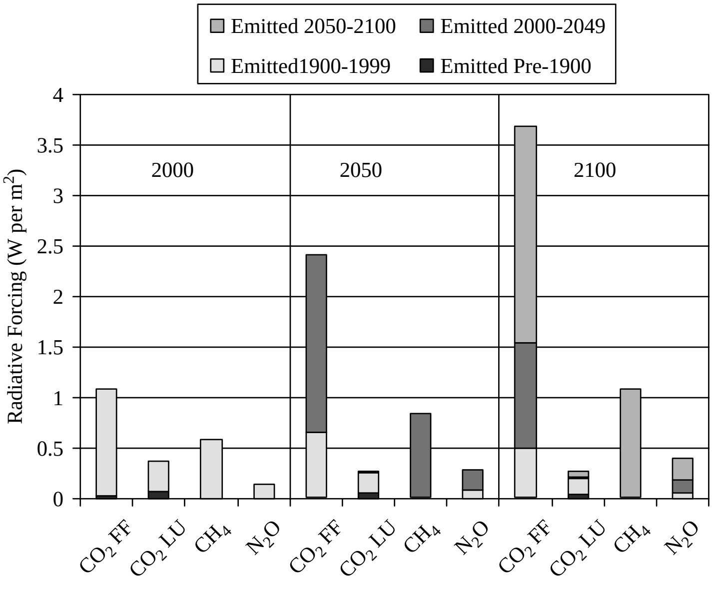


Figure 2.
Radiative forcing under the B2 emissions scenario from carbon dioxide from fossil fuel burning (CO_2 FF) and land use change (CO_2 LU), methane (CH_4), and nitrous oxide (N_2O). Colors correspond to the date of emission

Proposed architecture for the post-2012 agreement

The fundamental objective of the next agreement should be to limit the maximum commitment to future warming to no more than 2-2.5°C above pre-industrial temperature. This upper limit represents the recent crystallization of scientific understanding around the idea that a warming above this level would likely cause large areas of the Greenland ice sheet to melt, would put the West Antarctic ice sheet at substantial risk, and would cause widespread disruption to global ecosystems and the hydrologic cycle (SEG, 2007; IPCC, 2007b; MacCracken, 2008a).

The 2-2.5°C limit corresponds to a net radiative forcing in the atmosphere of between 2.5 and 3.1 $\mathrm{Wm^{-2}}$ above pre-industrial, although uncertainty over the climate sensitivity parameter means this value could be somewhat higher or lower[4]. This compares to a current net forcing of 1.6 $\mathrm{Wm^{-2}}$ above pre-industrial, a combination of a positive forcing of 3.2 $\mathrm{Wm^{-2}}$ from increased greenhouse gas concentrations, and a negative forcing of 1.6 $\mathrm{Wm^{-2}}$ from the estimated cooling influence of sulfate aerosols (IPCC, 2007a)[5]. It will be important that temperature and forcing limits of acceptable climate change are defined in a future climate agreement in order to provide direction to the process of negotiating long-term, global emissions limits.

The architecture proposed in this paper for the needed post-Kyoto agreement is based on the existing cap-and-trade framework, with expanded membership, deeper emissions cuts, and a longer commitment term. As in the Kyoto framework, national responsibilities for emissions reduction are differentiated based on per-capita GDP, but cuts in the emissions of short-lifetime pollutants are leveraged to take advantage of the timely and cost-effective mitigation options offered by control of these greenhouse gases, and to catalyze the participation of key middle-income countries in a way that, we suggest, should be acceptable to both middle- and high-income nations (see MacCracken, 2008b for a succinct summary of proposal commitments).

Nations would be grouped into three categories, replacing the present system of Annex 1 (generally referred to as developed nations) and Annex II (generally referred to as developing nations). This reflects the large variation in economic development that exists in the Annex II group. The following threshold values are suggested as category definitions, roughly following World Bank (2008) groupings of low- and lower-middle-income, upper-middle-income, and high-income nations:

(1) high-income nations, having a per capita GDP of more than $10,000 in 2005;

(2) middle-income nations, having a per capita GDP of between $3,000 and 10,000; and

(3) low-income nations, having a per capita income of less than $3,000.

Graduation between groups would be based on both these economic thresholds, and on additional per-capita emissions thresholds that could be defined as part of the negotiations.

The responsibilities for emissions limitations[6] would vary by category and time, such that:

(1) High-income nations, because of their historic contribution to the present level of greenhouse gas concentration, their generally high per-capita emissions, and their greater economic capacity, would assume responsibility for the largest emission reductions in the near-term, committing to steep cuts in emissions of all

greenhouse gases. Net emissions (so allowing credit for documented biologic or geologic sequestration) need to be roughly 80 per cent below year 2000 emissions by 2050, a level consistent with the recommendation of the Stern (2007) report. While a fraction of these cutbacks could be accomplished by financing emissions reductions in middle and low-income nations, part of the burden of high-income nations is to demonstrate that a high-income society can function with a very low level of emissions; otherwise, there is no practical or moral basis for expecting action by others. Because of this, purchasing of emissions credits from low- and middle-income countries should be capped at perhaps 10-15 per cent of emission reduction commitment. Beyond 2050, it is likely that further emissions cuts on the order of 50 per cent will be required to keep warming below the threshold level, but this time frame will likely be beyond the scope of the post-Kyoto agreement.

(2) Middle-income nations, including major emitters such as China, India, Indonesia, and Brazil, that are presently responsible for the rapid growth in annual global emissions, will be critical to the success of the climate-stabilization effort. These nations would have a two-part commitment:

- The first part would be binding commitments to sharp reductions (on the order of 80 per cent by 2050) in emissions of CH_4, soot, and the pollutants that contribute to formation of tropospheric ozone. These commitments are key to the lifetime-leveraging strategy, as they will cause early and substantial reductions in radiative forcing but can be done at relatively low cost and will have substantial benefits beyond climate mitigation (Ramanathan and Carmichael, 2008; CCSP, 2008; Tol *et al.*, 2003). For example, many cities in the developing world suffer from air pollution problems that could be partially alleviated by reducing soot and ozone concentrations. Such measures would be consistent with Millennium Development Goals and could be politically acceptable to governments and people in middle-income countries. Other actions such as capturing methane from landfills or pipelines, and improving combustion efficiency to reduce soot emissions are efficiency measures that can have a relatively short payback time. Action on these "low-hanging fruit" commitments, which nevertheless have substantial climate benefits, would help to persuade hesitant high-income countries that the key middle-income nations are serious about participating in the global fight against climate change.
- The second part of the commitment would be sectoral intensity targets for fossil fuel emissions, in place of an absolute cap. Nations in this category would agree to adopt targets that would steadily improve the carbon-intensity of energy-intensive industries such as aluminum, paper, cement, steel, petrochemicals, and glass, ultimately aiming toward the highest industry standards. These improvements will likely have positive impacts on competitiveness, especially if global energy prices continue to increase, and several governments, notably China, already have energy-intensity targets in place (Pew Center on Global Climate Change, 2007).

(3) Low-income nations would have the least restrictive commitments. They would have no absolute cap on emissions but would adopt aspirational targets consistent with sustainable development and the Millennium Development Goals. These could include reducing soot from burning traditional biofuels

> (generating substantial public health improvements) as well as targets for avoided deforestation. Nations that join the agreement by setting and working toward such targets would benefit from participation in the global carbon market through a certified emissions reduction program similar to the current clean development mechanism (CDM).

As countries develop economically, they would, over time, "graduate" into the stricter emission-reduction regimes. For example, a low-income country under this proposal would agree to cap and reduce short-lifetime emissions (at a moderate rate of approximately 1 per cent per year) once it passed the threshold per-capita GDP definition of a middle-income nation. Similarly, middle-income countries would agree to reduce their long-lived greenhouse gas emissions at a comparable rate once their per-capita GDP was high enough to qualify.

In order to incentivize low-carbon development and to improve the equity of the proposal, we suggest that there be double graduation thresholds: one based on per-capita GDP and one on per-capita emissions. A country would have to pass both before entering the more restrictive regime. This would provide some incentive for a country to follow a low-carbon development path because such a low-emission country would be able to delay increased regulation beyond the per-capita GDP threshold.

Maintaining equity while reducing greenhouse gas emissions

At the heart of the current climate impasse is a recognition that, since the start of the Industrial Revolution, the developed nations have used the abundant and inexpensive energy from fossil fuels to power their economic development, and in doing so have caused the lion's share of the current climate problem. At the same time, a scenario in which the rest of the world achieved the OECD-level of current per-capita emissions (Marland *et al.*, 2007) before reducing them would be disastrous for the climate, resulting in a temperature increase far in excess of the 2-2.5°C threshold of dangerous climate change. In this context, any agreement that effectively prevents climate change by restricting the emissions of middle- and low-income countries might be considered "unfair" to the developing world because it will impose a constraint on development, for a global good, that richer nations did not face. To responsibly address this concern, it is important that equity considerations are at the heart of the post-Kyoto agreement. Having an architecture that is widely regarded as "fair" (i.e. one that is consistent with certain fundamental and widely-held equity principles) is not simply desirable, it is a basic prerequisite if the agreement stands any chance of being agreed to by the governments and public of negotiating countries.

The most commonly cited principles of equity in discussions of climate mitigation include the responsibility to mitigate (those with largest emissions mitigate the most) and the capacity to mitigate (those with the most resources mitigate the most) (Lange *et al.*, 2007). Because of the historic link between fossil-fuel use and economic growth, these two measures are somewhat correlated (richer countries tend to have higher per-capita emissions) but this link is not absolute. By linking the graduation thresholds that separate countries with increasingly-restrictive emission-reduction requirements to both per-capita emissions (a measure of responsibility) and per-capita GDP (a measure of capacity), these two equity considerations are explicitly incorporated into this proposal. Even though countries in each class are not further differentiated on the basis of responsibility or capacity (each member has to reduce the same proportion of emissions), the transparency of this basic system is preferable to a more complex emission-reduction formula that would be liable to manipulation and dilution.

Additional equity in this proposed agreement comes from assigning primary responsibility for the early reductions in long-lived greenhouse gas emissions, particularly fossil-fuel CO_2 emissions to the high-income nations. The dominance of energy-related CO_2 emissions in policy discussion reflects an acknowledgement that this issue is both critical to limiting long-term climate change and is the most difficult to solve. This proposal would shift the burden for early reductions in these emissions (which do need to happen if climate change is to be contained to an acceptable level) as much as possible onto the high-income nations. These countries would be responsible for the basic development and deployment of low-carbon energy sources and would bear the burden of demonstrating how economically-developed societies could exist with very low per-capita carbon emissions.

In contrast, middle-income countries would initially participate in the global climate agreement by controlling only the short-lived greenhouse gases, reductions of which tend to have ancillary benefits, and to be more cost-effective. Additionally, most of these emission-reductions can be achieved using technology that already exists. These nations would only tackle more challenging CO_2 reductions later on, once the technology is better established and, presumably, less expensive.

Promoting cost effectiveness

In combination with equity, cost effectiveness will be a crucial test for evaluating a climate agreement architecture. While it is perfectly possible that a non-cost-effective architecture could be negotiated, effective implementation and compliance, already a problem with the Kyoto Protocol, will be even more unlikely if costs are significantly higher than they could be. Including mechanisms to improve the cost effectiveness of the agreement will also likely improve the chances of the agreement being attractive to the governments of high-income nations, which will bear a large fraction of the initial costs of climate mitigation.

True cost effectiveness requires that the marginal cost of emissions abatement be equalized across all countries, industries, and gases. This can be achieved either through a wide-reaching cap and trade system, or by implementing a universal carbon tax. Cost effectiveness also requires that abatement of different greenhouse gases be interchangeable, achieved in the current agreement by comparing regulated gases through conversion to CO_2-equivalents using the 100-year global warming potential (GWP).

In this proposed lifetime-leveraging architecture, however, reductions in emissions of short-lived gases are explicitly specified as a way of actually reducing radiative forcing. The short atmospheric lifetime of some of these pollutants (particularly soot and tropospheric ozone) as well as their complex chemistry means that they are fundamentally different from, and so not readily exchangeable with, the long-lived greenhouse gases such as CO_2.

To the extent that there will not be a single, universal abatement price, the approach suggested here will not be absolutely cost-effective. However, good evidence already exists that reducing soot and ozone concentrations will be some of the least expensive ways of limiting global warming. Both of these are air pollutants and are already regulated in developed countries because of their impacts on human health and natural systems. The technology to reduce concentrations of these pollutants already exists and has been deployed in rich countries, so transfer to other parts of the world should be relatively inexpensive. Additional benefits from reducing mortality and morbidity from air pollution make it likely that these measures would have a negative net cost. For example, Ramanathan and Carmichael (2008) estimate that simply replacing biofuel cooking in South and East Asia with clean technologies would reduce black carbon heating in the regions by 75 and 30 per cent, respectively, and would dramatically reduce the hundreds of thousands of annual deaths and respiratory illness from indoor air pollution.

Because of the importance of this issue, two key aspects of cost-effectiveness, emissions trading and clean development are discussed more fully in the following sections.

Emissions trading

Under the Kyoto Protocol, all regulated gases can be traded interchangeably by conversion to CO_2-equivalents using the 100-year GWP (UNFCCC Decision 18, COP 7). The CO_2-equivalent of a given gas takes into account both the degree to which different molecules intensify the greenhouse effect, and the relative lifetimes of each gas. For example, out to 20 years after emission, a unit mass of atmospheric CH_4 is 72 times as effective at trapping heat as a comparable mass of CO_2; however, because the injected CH_4 is removed much more rapidly than the CO_2, the equivalency drops to only 25 when considering the cumulative effects over 100 years (IPCC, 2007a).

Several studies (Reilly *et al.*, 1999; Manne and Richels, 2000) have documented the limitations of comparing gases using only the CO_2-equivalent metric, noting that it particularly tends to undervalue the contribution of methane over the timescales of interest. For example, Reilly *et al.* (1999) compared two scenarios in which emissions were reduced by the same amount of CO_2-equivalents, in one case using only CO_2 and in the other using the cost-effective mix of Kyoto gases. When emissions cuts were substantial, they found the multi-gas approach produced a temperature rise in 2100 less than half of the supposedly-equivalent, CO_2-only approach.

Essentially, equating gases based on the 100-year GWP significantly reduces the value of reductions in the emissions of methane because its atmospheric lifetime is only 12 years (IPCC, 2007a). However, because this rapid removal means cuts in emissions can lead to an early decrease in the global warming influence, we suggest that methane-reduction is in fact more valuable than indicated by the CO_2-equivalent (100-year GWP) calculation, precisely because of its relatively short lifetime.

Applying this principal generally, it is clear that emission reductions of short- and long-lived greenhouse gases (or aerosols) are not truly interchangeable; control of the former reduces the stock of gas in the atmosphere, while control of the latter prevents an increase in the stock over the timescales of interest. In a world where preventing dangerous climate change looks set to become increasingly urgent and increasingly difficult, this difference cannot be overlooked.

The authors propose that emissions trading be limited to the greenhouse gases with lifetimes of centuries or longer (CO_2, HFCs, N_2O etc) for which the CO_2-equivalent metric produces a good approximation of the relative warming influences over the timescales of policy interest. In the interests of cost-effectiveness, we suggest that methane could also be traded with longer-lived gases but conversion should be based on the 20-year GWP, which better captures the value of the rapid reduction in radiative forcing that methane emission reduction produces. The complicated chemistry, localized distribution, and difficulty of ensuring a permanent reduction of the very short-lived pollutants (specifically tropospheric ozone and soot) means that they are generally unsuited to an international trading program[7].

While it is true that international trading of permits can lead to more cost-effective outcomes, limits do need to be imposed on the extent of trading. The authors propose that emission reduction requirements for countries in a given income category be traded freely between other countries in that group, but that there be a limit of 15 per cent of the reduction requirements that can be met using certified emission reduction credits from countries with less strict regulation (equivalent to the CDM under the current regime). This is because it is essential that there be a strong push from high-income nations to develop the technologies that will allow them, and eventually all nations, to sharply reduce their emissions over the next few decades, and also because of the problems with additionality that have been identified with the CDM as it currently stands.

Supporting clean development

Because this proposed framework encourages the participation of low- and middle-income countries by not imposing caps on the long-lived greenhouse gas emissions in the near-term, the mechanisms to support clean development will need to be particularly strong and effective. CDM financing will need to increase substantially, which will to some degree occur naturally as the carbon market expands and the accreditation process is streamlined. In addition, given the importance of robust certification measures of emission reductions, particularly for the large, rapidly-developing middle-income countries, the CDM process for these nations should be reformed so as to remove current perverse incentives for the countries and industries that stand to profit from it, and to provide real baselines, rather than the current hypothetical, and hence ultimately unverifiable baselines.

The CDM for middle-income countries would be reformed to move away from the project-by-project approach and toward national accounting measures for these middle-income countries. Participating countries would agree on a national baseline for business-as-usual emissions for any greenhouse gases that are not capped under the agreement. Reductions below this baseline would be credited and could be sold to regulated countries to satisfy their emission-reduction goals, or could be banked by developing countries themselves against future reduction requirements once they pass the threshold level of per-capita GDP and per-capita emissions. This system, where credits are issued based on relation to a hypothetical but given baseline would ensure the credits represent a real and quantifiable reduction in emissions.

Negotiating the business-as-usual baseline will undoubtedly be difficult: the baseline will need to be at once high enough to persuade developing countries to aim for an emissions pathway below that level, and yet low enough that global emissions collectively do not exceed 2.5°C of warming. Critically, however, this baseline could be used to incentivize the participation of important middle-income countries: a baseline higher than the projected business-as-usual essentially amounts to giving away valuable carbon-credits. While clearly not ideal environmentally, this tool could theoretically be used to encourage participation of certain large-emitters whose non-participation would threaten the entire agreement process.

This modified CDM could provide some financial incentive for a country to follow a lower-carbon development pathway, but other mechanisms could help to facilitate this. CDM trading should be closely tied to technology transfer, so that the process results not just in the development of carbon credits, but in increased capacity in the host country that could generate further reductions. One way of doing this is to have a premium on those carbon credits that are tied to verified capacity building and technology transfer in the receiving country. Credit value would be generated not only for the emissions they help reduce, but for also the positive domino effect of technology transfer in further emission reductions.

In addition, improvements in sectoral efficiency for energy-intensive industries will be an important part of the middle-income countries' climate commitment. This should improve the environmental effectiveness and substantially lower the overall cost of the agreement by avoiding a widescale deployment of inefficient technology that would have to be removed and replaced once CO_2 emissions begin to be regulated. Many of the key middle-income countries already have domestic policies that mandate just such efficiency improvements. The Chinese Government, for example, in its 11th five-year plan (2006-2010), has set a national target for improving energy intensity by 20 per cent by 2010 (Pew Center on Global Climate Change, 2007). In India, the Bureau of Energy Efficiency (2008) was established in March 2002 as a statutory body under the Indian Ministry of Power to coordinate energy efficiency measures and reduce the energy intensity of India's economy.

While the existing CDM does have several problems, the advantage of a project-based approach is that it does not rely on the central government for inventorying emissions or for the implementation of national emissions-control policy. Since many of the LDCs lack the institutional capacity to comprehensively monitor and control emissions, the traditional, project-based CDM could be continued in the low-income countries that become party to the post-Kyoto agreement. This would allow these nations access to the carbon-trading mechanism but would likely only have a limited adverse climatic effect relative to the national baseline approach; to date only 280 out of 3,250 CDM projects have taken place in the least-developed countries (UNEP, 2008).

Incentives for participation and compliance

Mechanisms for encouraging participation (countries to sign the agreement) and compliance (countries to implement what they agree to under the agreement once signed) are major weaknesses of many proposed climate agreements (Aldy *et al.*, 2003). This is at least partly because the agreement will be between sovereign nation states and so these methods are inherently limited. To some degree, participation and compliance will need to be motivated by the desire to limit climate change. But, as many have noted, this is unlikely to be enough incentive for major middle-income emitters to join an ambitions climate agreement, and might not be enough to keep countries sticking to difficult and costly emission-reduction measures, even though committed to under and international agreement.

Part of the advantage of the lifetime-leveraging strategy is the fact that the early commitments from middle-income countries are related to measures that would likely be undertaken anyway as part of a development strategy. These include reducing air pollution, and improving combustion efficiency. This should ideally make participation more attractive to middle-income nations and, to a limited degree, reduce the extent of specific participation incentives needed to bring these key countries on board.

The most important specific measure in the proposed agreement that would encourage participation by low- and middle-income countries is the certified emissions reduction program. With the carbon market expected to grow to $3.1 trillion by 2020 (Point Carbon, 2008), and potentially substantially larger under a stronger post-2012 agreement, revenues from the CDM-type program will probably be substantial, even if it is responsible for a maximum of 10-15 per cent of emissions reductions. As suggested above, national baselines for key middle-income nations could be negotiated on a country-by-country basis as a way of incentivizing participation. In addition, any adaptation funding, either from specific pledges from OECD countries, or from a tax on traded emissions, could be made contingent on participation in the international agreement.

Encouraging compliance could be even more difficult than encouraging participation. Countries should have short-term (five years or so) targets to meet, which could steepen over the course of the agreement, in order to ensure they are on their way to achieving the long-term emissions reduction plan set out in the agreement. These targets could be used to evaluate whether or not a country is in compliance. Countries consistently out of compliance could become vulnerable to tariffs (scaled based on carbon-intensity) on energy-intensive imports, at the discretion of in-compliance, signatory countries. The authors believe that trade measures, which are now widely discussed as one of the only ways of imposing climate externalities beyond national borders and which were incorporated into the Lieberman-Warner Climate Security Act, are better used to address compliance issues rather than participation issues. Used this way, they stand a better likelihood of being WTO-compliant (Tarasofsky, 2008; World Bank, 2007) and of being generally perceived as fair.

Can lifetime-leveraging prevent dangerous climate change?

Preliminary analysis indicates that with ambitious (but very likely achievable) reductions in emissions, the lifetime-leveraging architecture described above can limit the increase in radiative forcing enough to prevent warming of more than 2-2.5°C. In carrying out this evaluation, we developed a relatively simple pulse-response model to calculate the time history of radiative forcing under various emissions scenarios based on the lifetime-leveraging approach[8].

For example, total warming commitment could be constrained to less than 2.5°C if the OECD countries undertook an ambitious target of reducing all greenhouse gas emissions 80 per cent by 2050 and a further 50 per cent by 2100, and middle-income countries undertook the same targets for the short-lived greenhouse gases. If these middle-income countries develop relatively efficiently under the intermediate B2 growth path (IPCC, 2000) and begin reducing long-lived greenhouse gas emissions by 1 per cent per year once they reach $10,000 per-capita GDP then, assuming an intermediate climate sensitivity of $0.8^{\circ}\mathrm{C/Wm}^{-2}$ (close to 3°C for a doubling of CO_2), warming should peak at less than 2.5°C above pre-industrial temperatures[9].

Figure 3 shows the fossil-fuel-related carbon emission pathway, per-capita emission pathway, and annual emission reductions below baseline for the four modeled world regions under this scenario. Although the developing regions of Asia, Africa and Latin America are responsible for the largest below-baseline reductions (Figure 3(c)), these do not begin until fairly late in the twenty-first century, and are therefore likely to be less costly than the earlier reductions undertaken by the OECD. Asia (as an average region) does not begin reducing CO_2 emissions until almost 2050, and the other developing regions until 2065. These regions will thus likely benefit from the technologies and experience developed by the OECD countries during their earlier emissions reduction. Per-capita emissions for all regions are converging toward equal values by 2100 (Figure 3(b)), and could be stabilized at the same amount in the early part of the twenty-second century.

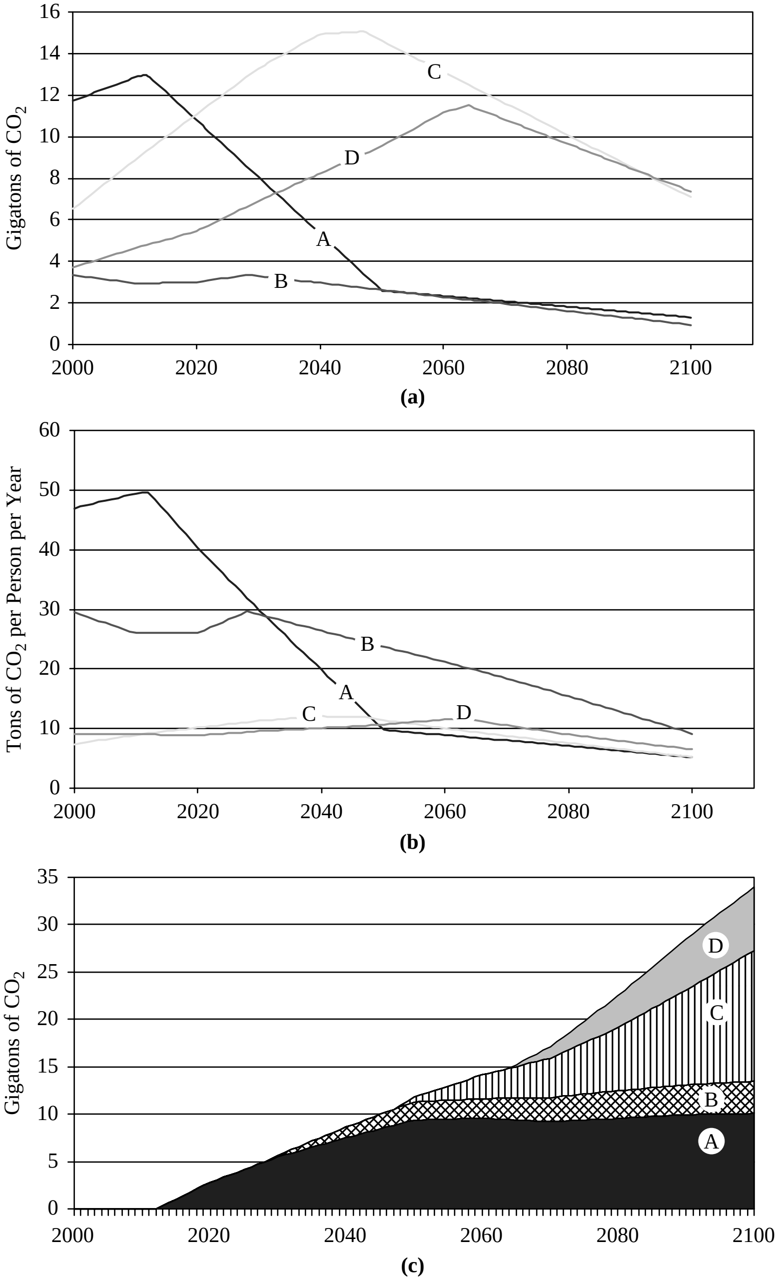
This modeling result admittedly does not take into account the effects of emissions leakage, whereby fossil-fuel intensive industries move from a regulated region to a non-regulated region to avoid the cost of compliance. A recent study of the effects of existing energy efficiency and emission-reduction measures on energy-intensive industries found that evidence for emissions leakage to date is equivocal at best (World Bank, 2007). Nevertheless, emissions-control regulations have so far been fairly lenient compared to what they will likely have to be in the future, and it could still be that emissions leakage would substantially reduce the efficacy of any agreement that did not impose caps on the emissions of all countries.

The structure of the proposed agreement, however, in which emissions reduction requirements are tied to GDP thresholds, could provide a negative feedback that would limit the impact of emissions leakage. The relocation of energy-intensive industry to developing countries constitutes economic development that will raise the GDP of the host nation, meaning that the threshold income level at which fossil-fuel emission regulation begins will be reached sooner than in the baseline scenario. A simple spreadsheet model used to estimate the strength of this feedback effect suggests that even if up to 50 per cent of "cut" emissions were to leak to non-regulated regions, cumulative emissions over the twenty-first century would increase by only 7 per cent. Since the climatic effect of emissions depends most strongly on the cumulative amount, rather than the timing of emissions (Matthews and Caldeira, 2008), it is unlikely that including the effect of emissions leakage would substantially reduce the climate-stabilizing benefits of the lifetime-leveraging architecture.

Summary and conclusion

Over the last decade, as the rate of climate change has accelerated, many natural systems, including the Arctic sea ice, the Antarctic ice shelves, and the Greenland ice sheet, have surprised scientists with the speed of their response to warming. The effects of climate change have been detected in ecosystems on every continent (Rosenzweig, 2008) and, given the inertia in the system and the possibility of substantial carbon-cycle feedbacks, it is becoming increasingly difficult to argue that the world is not already close to a degree of climate change that could generally be considered dangerous, if not catastrophic (SEG, 2007).

Given this context, the post-Kyoto climate agreement will be critical in determining the climatic burden that we place on future generations. The lifetime-leveraging architecture proposed in this paper has the double benefit of using the



Notes: Ⓐ– OECD, Ⓑ– former Soviet Union, Ⓒ– Asia, Ⓓ– Africa, Latin America and Middle East

Source: Baseline emissions from IPCC (2000)

Figure 3.
(a) Annual emissions of CO_2 from fossil fuel burning for four world regions under the proposed emissions reduction scenario; (b) per-capita emissions of CO_2 from fossil fuel burning for four world regions under the proposed emissions reduction scenario; (c) below-baseline (B2) reductions in CO_2 emissions from fossil fuel burning for four world regions under the proposed emissions reduction scenario

often-overlooked, short-lived greenhouse gases to both substantially decrease radiative-forcing ("buying time" to fully get to grips with more intractable CO_2 emissions), and to overcome the negotiations deadlock between high- and middle-income countries.

Reductions in the atmospheric burdens of tropospheric ozone, methane and soot represent an opportunity to significantly reduce the human-induced radiative forcing that is causing global warming. Moreover, much of the reduction in these emissions can be done at little cost, and in a way that is consistent with the broad development strategy of middle-income nations. In fact, the benefits of reducing soot and ozone concentration in term of improved public health will likely be larger than the benefits of mitigated climate change. This targeting of short-lived pollutants, combined with aggressive cuts in emissions from high-income countries, aspirational goals and CDM-participation from low-income countries, and improvements in energy intensity to slow the growth of energy-related CO_2 emissions in middle-income countries, should be enough limit peak temperature increase to less than 2-2.5°C above pre-industrial temperatures. If this can be done, and the radiative forcing then be gradually reduced from the peak levels in following decades, the objective of the UNFCCC, namely to avoid "dangerous anthropogenic interference with the climate", may be achieved.

Notes

1. All temperature increases in this proposal are given as the warming above the preindustrial baseline, even if this is not mentioned each time.
2. Calculated using radiative forcing given by the IPCC (2007a, p. 204) and assuming a climate sensitivity of $0.8°C/Wm^{-2}$ (approximately 3°C for a doubling of CO_2).
3. Radiative forcing is a useful measure for directly comparing diverse factors that affect the Earth's climate. Measured in Watts per meter squared (Wm^{-2}), the value describes the equivalent change in net solar irradiance at the tropopause (top of the troposphere) caused by a given climate driver (for example, an increase in greenhouse gas concentration or a change in albedo).
4. Note that, because it takes several decades for the global temperature to equilibrate with a change in radiative forcing, breaching the forcing threshold will not immediately lead to breaching of the temperature threshold. Rather the threshold is a stabilization target, indicating that the value should not be exceeded for a substantial length of time (more than a decade or so).
5. In the longer-term, the world should aim for stabilization at a maximum (and ideally well below) $3.1\ Wm^{-2}$ of positive forcing (rather than net forcing), which would likely require the removal of some long-lived greenhouse gases from the atmosphere. Exceeding the forcing threshold with long-lived greenhouse gases and then relying on the cooling effect of short-lived sulfates places an indefinite burden on future generations, requiring them to either continue emissions of sulfates that might otherwise be controlled to improve public health, or to launch a geoengineering project to otherwise sustain their cooling effect.
6. Because emissions of halocarbons are covered under the Montreal Protocol and subsequent conventions, their limitation is not considered here. It is instead assumed that limitations in halocarbon emissions will be aggressively pursued under that agreement (Velders *et al.*, 2007).
7. For example, ozone is not emitted directly, but is formed from the reaction of NO_x and volatile organic compounds. Soot is distributed extremely heterogeneously in the atmosphere and the effect of emissions reductions on atmospheric warming depends

partly on the ambient black carbon concentration and on the underlying surface albedo, hence differs from region to region, making international trading of emissions reductions problematic.

8. The model used is a simple four region Excel model that accounts for emissions of CO_2 from fossil fuel burning and deforestation, CH_4, N_2O, and the direct and indirect effects of sulfate. Past emissions are assembled with datasets from WRI (2007), Houghton (2003), Ramankutty and Foley (1999), Stern and Kaufman (1998), Olivier and Berdowski (2001) and Smith *et al.* (2004), with projected emissions from IPCC (2000) and lifetime and forcing equations from Hansen *et al.* (2007) and IPCC (2001, 1997). The complicated chemistry and spatial heterogeneity of tropospheric ozone and soot make them too difficult to include in such a simple model so reductions in radiative forcing will in fact be larger than suggested above under the proposed scenario; for an indication of the likely magnitude of these effects, see CCSP (2008).
9. Although the B2 scenario is intermediate in the suite of SRES storylines, the growth in emissions since 2000 has exceeded the high-end A1FI scenario (Canadell *et al.*, 2007). However, the B2 storyline might be roughly consistent with developing countries undertaking commitments to improve energy efficiency, as proposed above.

References

Aldy, J.E., Barrett, S. and Stavins, R.N. (2003), "Thirteen plus one: a comparison of global climate policy architectures", FEEM working paper, Vol. 64, July.

Baer, P. and Athanasiou, T. (2007), "Frameworks and proposals: a brief, adequacy and equity-based evaluation of some prominent climate policy frameworks and proposals", *Global Issues Papers*, Vol. 30.

BP (2007), *Statistical Review of World Energy 2007*, British Petroleum – BP, London.

Bureau of Energy Efficiency (2008), *About Us*, Bureau of Energy Efficiency, New Delhi, available at: www.bee-india.nic.in (accessed 21 June 2008).

Canadell, J.G., Pataki, D. and Pitelka, L. (2007), "Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks", *Proceedings of the National Academy of Sciences*, Vol. 104 No. 47, pp. 18866-70.

CCSP (2008), "Climate projections based on emissions scenarios for long-lived and short-lived radiatively active gases and aerosols", in Levy, H. II, Shindell, D.T., Gilliland, A., Schwarzkopf, M.D. and Horowitz, L.W. (Eds), *A Report by the US Climate Change Science Program and the Subcommittee on Global Change Research*, Department of Commerce, NOAA's National Climatic Data Center, Washington, DC.

Hansen, J., Sato, M., Ruedy, R., Kharecha, P., Lacis, A. and Miller, R. (2007), "Dangerous human-made interference with climate – a GISS modelE study", *Atmospheric Chemistry and Physics*, Vol. 7, pp. 2287-312.

Houghton, R.A. (2003), "Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000", *Tellus B*, Vol. 2, pp. 378-90.

IPCC (1997), in Houghton, J.T., Kram, A., Makarov, B., Sorensen, B., Yokobori, K. and Zhou, F. (Eds), *Technical Paper II: An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report*, Intergovernmental Panel on Climate Change – IPCC, pp. 41-2.

IPCC (2000), in Nakićenović, N. and Swart, R. (Eds), *Special Report on Emissions Scenarios (SRES)*, Intergovernmental Panel on Climate Change – IPCC, Cambridge University Press, Cambridge.

IPCC (2001), in Houghton, J.T., Ding, Y., Griggs, D., Noguer, M., van der Linden, P. and Xiaosu, D. (Eds), *Climate Change 2001: The Scientific Basis*, Intergovernmental Panel on Climate Change – IPCC, Cambridge University Press, Cambridge, pp. 800-23.

IPCC (2007a), in Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds), *Climate Change 2007: The Physical Science Basis*, Intergovernmental Panel on Climate Change – IPCC, Cambridge University Press, Cambridge.

IPCC (2007b), in Parry, M., Canziani, O.F. and Palutikof, J.P. (Eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Intergovernmental Panel on Climate Change – IPCC, Cambridge University Press, Cambridge.

Lange, A., Vogt, C. and Ziegler, A. (2007), "On the importance of equity in international climate policy: an empirical analysis", *Energy Economics*, Vol. 29 No. 3, pp. 545-62.

MacCracken, M.C. (2008a), "Prospects for future climate change and the reasons for early action", *Journal of the Air and Waste Management Association*, Vol. 58, pp. 735-86.

MacCracken, M.C. (2008b), "Prospects for future climate change and the reasons for early action: a summary of the 2008 critical review", *The Magazine for Environmental Management*, June.

Manne, A.S. and Richels, R.G. (2000), "A multi-gas approach to climate policy – with and without GWPs", FEEM Working Paper, No. 44.

Marland, G., Boden, T.A. and Andres, R.J. (2007), "Global, regional, and national fossil fuel CO_2 emissions", *Trends: A Compendium of Data on Global Change*, Oak Ridge National Laboratory, Information Analysis Center, Oak Ridge, TN.

Matthews, H.D. and Caldeira, K. (2008), "Stabilizing climate requires near-zero emissions", *Geophysical Research Letters*, Vol. 35, L04705.

Meinshausen, M. (2006), "What does a 2°C target mean for greenhouse gas concentrations? A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates", in Schellnhuber, J.S., Cramer, W., Nakicenovic, N., Wigley, T.M.L. and Yohe, G. (Eds), *Avoiding Dangerous Climate*, Cambridge University Press, New York, NY, pp. 265-79.

Olivier, J.G.J. and Berdowski, J.J.M. (2001), "Global emissions sources and sinks", in Berdowski, J., Guichert, R. and Heij, B.J. (Eds), *The Climate System*, A.A. Balkema and Swets & Zeitlinger Publishers, Lisse, pp. 33-78.

Pew Center on Global Climate Change (2007), "Climate change mitigation measures in the People's Republic of China", available at: www.pewclimate.org

Point Carbon (2008), "Carbon market transactions in 2020: dominated by financials?", *Carbon Market Analyst*, 21 May.

Posner, E.A. and Sunstein, C.R. (2008), "Justice and climate change", Harvard Project on International Climate Agreements, Discussion Paper 08-04.

Ramanathan, V. and Carmichael, G. (2008), "Global and regional changes due to black carbon", *Nature Geoscience*, Vol. 1, pp. 221-7.

Ramankutty, N. and Foley, J. (1999), "Estimating historical changes in global land cover: croplands 1700-1992", *Global Biogeochemical Cycles*, Vol. 13, pp. 997-1027.

Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, H., Jacoby, H., Kicklighter, D. and Melillo, J. (1999), "Multi-gas assessment of the Kyoto Protocol", *Nature*, Vol. 407, pp. 549-55.

Rosenzweig, C. (2008), "Attributing physical and biological impacts to anthropogenic climate change", *Nature*, Vol. 453, pp. 353-7.

SEG (2007), "Confronting climate change: avoiding the unmanageable and managing the unavoidable", in Bierbaum, R.M., Holdren, J.P., MacCracken, M.C., Moss, R.H. and Raven, P.H. (Eds), *Scientific Expert Group on Climate Change – SEG*, prepared for the United Nations Commission on Sustainable Development by Sigma Xi, Research Triangle Park, NC, and the United Nations Foundation, Washington, DC.

Smith, S.J., Andres, R., Conception, E. and Lurz, J. (2004), "Sulfur dioxide emissions: 1850-2000", JGCRI Report, Pacific Northwest National Laboratories-14537.

Stern, D. and Kaufman, R. (1998), "Annual emissions of global anthropogenic methane: 1860-1994", *Trends Online: A Compendium of Data on Global Change*, CDIAC Oak Ridge National Laboratory, Oak Ridge, TN.

Stern, N. (2007), *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge.

Sugiyama, T. and Deshun, L. (2004), "Must developing countries commit quantified targets? Time flexibility and equity in climate change mitigations", *Energy Policy*, Vol. 32, pp. 697-704.

Tarasofsky, R.G. (2008), "Heating up international trade law: challenges and opportunities posed by efforts to combat climate change", *Climate Change Law Review*, Vol. 1, pp. 7-17.

Tol, R.S.J., Heintz, R.J. and Lammers, P.E.M. (2003), "Methane emission reduction: an application of FUND", *Climatic Change*, Vol. 57, pp. 71-98.

UNDP (2007), *Human Development Report 2007/2008: Fighting Climate Change*, United Nations Development Programme – UNDP, New York, NY.

UNEP (2008), *CDM Pipeline*, United Nations Environment Programme, New York, NY, available at: cdmpipeline.org/cdm-projects-region.htm#1 (accessed 1 May 2008).

Velders, G.J.M., Andersen, S.O., Daniel, J.S., Fahey, D.W. and McFarland, M. (2007), "The importance of the Montreal Protocol in protecting climate", *Proceedings of the National Academy of Sciences*, Vol. 104, pp. 4814-19.

World Bank (2007), *International Trade and Climate Change: Economic, Legal and Institutional Perspectives*, World Bank, Washington, DC.

World Bank (2008), *World Bank List of Economies*, World Bank, Washington, DC, available at: http://go.worldbank.org/K2CKM78CC0 (accessed 17 October 2008).

WRI (2007), *Carbon Analysis Indicator Tool, Version 3.0*, World Resources Institute – WRI, Washington, DC, available at: cait.wri.org

Further reading

Stephens, B.B., Gurney, K.R. and Tans, P.P. (2007), "Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO_2", *Science*, Vol. 316, pp. 1732-5.

Wigley, T.M.L. (2005), "The climate change commitment", *Science*, Vol. 307, pp. 1766-9.

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Appendix G

CENTER FOR A COMPETITIVE WASTE INDUSTRY
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April 14, 2010

Mr. Leif Hockstad
U.S. Environmental Protection Agency
Climate Change Division (6207J)
1200 Pennsylvania Ave., NW
Washington, DC 20460

Re: 2010 Draft U.S. Greenhouse Gas Inventory Report
Comments by the Center for a Competitive Waste Industry

Dear Mr. Hoskstad:

Thank you for the opportunity to provide comments by the Center for a Competitive Waste Industry on the U.S. Environmental Protection Agency's (EPA) 2010 Draft U.S. Greenhouse Gas Inventory Report (Draft). As someone formerly retained by EPA to review its landfill gas protocols, and someone independent of the landfill industry, we hope that you find the recommendations useful.

In summary, we recommend that the Draft be changed as follows:

(1) *Global warming potential.* Include in the table showing each sector's responsibility for anthropogenic greenhouse gas emissions the applicable value when current instead of obsolete Global Warming Potential multipliers are used.

(2) *Short-term strategies.* Employ a two-pronged strategy that includes a short-term along with the long-term approach in reported inventory values.

(3) *First Order Decay Model.* Replace the First Order Decay Model, which fails to account for internal moisture levels critical for gas generation, with a revised model that does.

Some of the recommendations can be accommodated within the Intergovernmental Panel on Climate Changes' (IPCC) Guidelines,[1] and others may not. For those that may not, nothing in the Guidelines precludes an Annex I signatory to the United Nations Framework Convention on Climate Change (UNFCCC) treaty from providing supplemental information as part of the formal inventory. For the future, inasmuch as EPA's views have guided the development of the IPCC's 1996 and 2006 support documents for landfills, and to the extent that the facts presented are correct and its policies, constructive, the agency can pursue their inclusion in future updates of the Guidelines.

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[1] IPCC, *2006 Guidelines for National Greenhouse Gas Inventories* (2006).

I. GENERIC COMMENTS

A. Global Warming Potential

The reported anthropogenic warming impacts from the different greenhouse gases (GHGs) are converted into a common carbon dioxide (CO_2) equivalent basis by the use of Global Warming Potential (GWP) multipliers, which is a set of factors for each GHG. Of import, these factors are not immutable, but rather are periodically updated to comport with the current state of knowledge about such complex factors as indirect effects.

However, even though the Draft tracks Guidelines, it uses GWP factors that were actually published in 1996 (but, in fact, actually estimated several years prior to that publication date), and ignores the last 15 or more years of updated values that reflect what is now known.

According to the Draft, obsolete data was relied upon because:

> "The UNFCCC reporting guidelines for national inventories were updated in 2006, but continue to require the use of GWPs from the IPCC Second Assessment Report (SAR) (IPCC 1996). This requirement ensures that current estimates of aggregate greenhouse gas emissions for 1990 to 2008 are consistent with estimates developed prior to the publication of the IPCC Third Assessment Report (TAR) and the IPCC Fourth Assessment Report (AR4)."[2]

There may be value in having a consistent time series, but there is an even greater value in providing an inventory for 2010 that reflects the current state of knowledge. Otherwise, if a consistent time series were the only consideration reflected in the inventory, decision-makers, who use the inventory to triage priorities for government action, will be presented with obsolete information about the different GHG gases that does not reflect what we now know about how those gases' impact climate.

As a salient example, the GWP for methane is assumed to be 21 times CO_2, which is what was known in the years prior to 1996, almost 20 years ago.

Since then, in AR4 (published in 2007), methane's GWP (on a 100 year basis) was 25 times CO_2,[3] and the most recent information from the National Aeronautics and Space Administration (NASA) is that methane has 34 times the long-term warming impact of CO_2.[4] The reason why this value changes is due to the growing knowledge about the *indirect* impacts of methane on radiative forcing, first in terms of stratospheric water vapor, then tropospheric ozone, and, most recently, mixing with aerosols.

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[2] Draft, at p. ES-3.

[3] IPCC, *Fourth Assessment Report*: Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing (2007), at p. 212. That value, in turn, was several years out of date when FAR was finally published in 2007, and, as indicated next, has now been supplanted.

[4] Drew Shindell, "Improved Attribution of Climate Forcing Emissions," 326 SCIENCE 716 (2009).

To use a GWP for methane in 2010 of 21, when the most reliable value today is *62% greater*, has the effect of grossly undercounting the impacts of sources of anthropogenic methane emissions compared to sources of other greenhouse gases. That cannot but gravely distort society's response to a much more serious threat and result in a misapplication of resources to avert climate change, especially in the context of near-term impacts described next.

Therefore, we recommend that the final inventory include the existing table that shows a consistent time series from 1990 to 20008 (as modified by the other comments that follow below) to comport with the Guidelines. But, then the table should include an additional right-hand column showing the 2008 data converted to the current data on GWPs. Nothing in the Guidelines precludes or discourages more accurate supplementation.

There is an enormous value in incorporating the most reliable data into decision-making, and the Draft fails to accord this need its due. If the definition of "authoritative" were somehow to be twisted to mean "hopelessly out-of-date," the practical utility of the entire exercise would be called into in question and resemble nothing so much as "fiddling while the world burns." The difference between 1996's very preliminary state of knowledge then, which was largely ignorant of methane's indirect effects, and today, more than 15 years later, is simply too great to ignore on the grounds of nothing more substantive than bureaucratic inertia.

B. Short Term Climate Impacts

Each GHG has a different residence time in the atmosphere before they decay or are absorbed, from 0.38 years for methylene chloride to 50,000 years for PFC-14, with 12 years for methane.[5] In order to equate each GHG to CO_2, the same residency must be assumed to perform the calculation, even though, in fact, the gases remain airborne for vastly different periods. The current convention for that common denominator is 100 years, which initially was the proxy for CO_2's duration in the atmosphere.[6]

However, global warming does not proceed linearly over time, but rather, accelerated by positive feedback loops, changes in climate can ramp up rapidly and irreversibly in the near term as tipping points are crossed.[7] In response to this implacable reality, a growing body of scientific opinion has more recently urged a two-pronged strategy to address those points of no return. This is not to suggest either ignoring or demoting the long-term consequences. Rather, the recommendation is only to recognize that, in order to sustain the viability of human institutions until that far-off day arrives, we must first insure that quick action is taken to avert crossing key tipping points, after which further remedial action is no longer possible:

> "Policy must evolve and incorporate the emerging science in order to be effective. There is a growing need to create a two-pronged framework capable of

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[5] See NOTE 3, *supra*.

[6] *Id*.

[7] Timothy M. Lenton, et al., "Tipping elements in the Earth's climate system," 105 PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES 6, at pp. 1786-1793.

> not only mitigating long-term climate change but also managing the magnitude and rate of change of near-term R[adiative] F[orcing]. Short-lived pollutants (black carbon and tropospheric ozone) and medium-lived pollutants (methane) account for more than half of the positive RF generated in years 1 to 20."[8]

Once the need for such a two-pronged strategy is understood, then attention quickly turns to methane as the most important GHG for that approach, as Dr. Jackson alludes to in his above statement. According to climate scientists at the National Aeronautics and Space Administration (NASA), the combination of methane's warming potency, and its short lifetime in the atmosphere, plays an especially critical role in the near term when we confront those critical tipping points. Methane's residency is 12 years, and, when measured in the next 20 instead of 100 years, is 105 times as powerful as CO_2:[9]

> "[F]easible reversal of the growth of atmospheric [methane] and other trace gases would provide a vital contribution toward averting dangerous anthropogenic interference with global climate...[Methane] deserves special attention in efforts to stem global warming...Given the difficulty of halting near-term CO_2 growth, the only practical way to avoid [dangerous interference] with climate may be simultaneous efforts to reverse the growth of [methane].[10]

Similarly, Robert Watkins, the co-chair of the IPCC's Third Assessment, recently wrote in the disappointing aftermath of Copenhagen:

> "This month's Copenhagen talks focused on the leading climate change culprit: CO_2. But reversing global temperature increases by reducing carbon emissions will take many decades, if not centuries. Even if the largest cuts in CO_2 contemplated in Copenhagen are implemented, it simply will not reverse the melting of ice already occurring ...The most obvious strategy is to make an all-out effort to reduce emissions of methane. Methane's short life makes it especially interesting in the short run, given the pace of climate change. If we need to suppress temperature quickly in order to preserve glaciers, reducing methane can make an immediate impact. Compared to the massive requirements necessary to reduce CO_2, cutting methane requires only modest investment. Where we stop methane emissions, cooling follows within a decade, not centuries. That could make the difference for many fragile systems on the brink."[11]

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[8] Stacy C. Jackson, "Parallel Pursuit of Near-Term and Long-Term Climate Mitigation," 326 SCIENCE 526 (2009), excerpted from 526-527. See, also, Alissa Kendall, et al., "Accounting for Time-Dependent Effects of Biofuel Life Cycle Greenhouse Gas Emissions Calculations," *Environ. Sci. Techn*. (August 14, 2009), p. 6907.

[9] See note 3, supra.

[10] James Hansen, "Greenhouse gas growth rates", 101 PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES 46 (November 16, 2004), p. 161094.

[11] Robert Watson and Mahamed El-Ashry, "A Fast, Cheap Way to Cool the Planet," *The Wall Street Journal* (December 29, 2009).

Indeed, EPA, itself, has long observed methane's critical importance for addressing short term climate impacts:

> "This relatively short lifetime makes methane an excellent candidate for mitigating the impacts of global warming because emission reductions could lead to stabilization or reduction in methane concentrations within 10-20 years."[12]

For these reasons, we strongly urge the Draft to include an additional chapter on short-term impacts (i.e. the next twenty years), along with the 100-year inventory values, and the GWP factors that are applicable to that time frame, along with reference to the greenhouse gases most important to short term climate action plans. In the case of methane, as noted, that would be a multiplier of 105 times CO_2's warming potential when using the latest data, and 72 times CO_2's, when using the data from AR4. This would enable decision-makers to assess where their short-term climate action plans should be most effectively directed.

This additional supplementation also comports fully with the IPCC protocols. The Second Assessment stated that while the UN Framework held there should be one set of consistent 100 year based GWP values across reporting nation's inventories, it also specifically provided that "[p]arties may also use other time horizons."[13]

II. LANDFILLS

As discussed in Chapter 8 of the Draft, along with Annex 3.1, landfills are among the significant sources of GHGs associated with climate change, because organic discards, which are half or more of total discards, if not separated at the source, are most often buried. In the oxygen-starved environment of a sealed landfill, food scraps, soiled paper, grass clippings, leaves, brush and other organic matter decompose anaerobically under the influence of methanogenic microbes. These thrive in the absence of oxygen, and create methane as a byproduct of decomposition.

Because modern lined landfills can extend for hundreds of acres in extent and rise hundreds of feet above grade, gas generated inside the waste body flows out into the atmosphere through myriad routes that defy measurement. This includes not only through cracks, tears and broken seams at the surface and along the sides and top, but also conveyed along the bottom of a facility following leachate collection gravel trenches and piping, wherever there is a path of least resistence.[14]

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[12] EPA, *U.S. Methane Emissions 1990 – 2020: Inventories, Projections, and Opportunities for Reductions* (EPA430-R-99-013, 1999), at p. 1-2.

[13] EPA, *Greenhouse Gases and Global Warming Potential Warming Values* (April 2002), at p. 9.

[14] George Tchobanoglous, *Integrated Solid Waste Management* (McGraw Hill, 1993), at p. 394. Memorandum to Brian Guzzone, EPA, from Chad Leatherwood, Eastern Research Group, Inc., dated November 18, 2002, re: Review of Available Data and Industry Contacts Regarding Landfill Gas Collection Efficiency (Leatherwood Memo), at p. 2.

In an attempt to overcome this lack of data, the process underlying the Annex's description purports to use the following mass balance equation that is calculated for each year:

$$\left| \text{Gas released} = \text{Gas generated} - \text{Gas captured} - \text{Gas oxidized} \right| \quad \textbf{(1)}$$

As discussed below, the problems with this attempt to represent reality are:

(1) ***Incorrect Modeling.*** Only one of the three terms to the right, Gas Captured, is known. Two are only modeled, not observed, values, namely Gas Generation and Gas Oxidized.[15] To estimate the unknown Gas Generation in order to then estimate Gas Released, a model is used which is inapplicable to the particular and unique conditions of a lined landfill and fails to include a coefficient for the most critical independent variable involved in decomposition of buried wastes, the level and distribution of essential moisture. Moreover, many of the landfill input data appears to be incorrect.

(2) ***Incomplete Landfill Phases.*** Gas generation from wastes interred today continue for decades into the future at a rate that varies with five different phases in a landfill's life that affects the level and distribution of essential moisture, all of which is ignored by the Draft's methodology.

(3) ***Oxidation Misapplied.*** The studies used to estimate oxidation are inapplicable to lined landfills.

Most of the controverted modeling turns on the equation used in the Draft to estimate Gas Generated, which is explained first.

A. Modeling

EPA first estimates the amount of annual Gas Generated based upon modeling by using a First Order Decay (FOD) equation, which in its simplified form is expressed:[16]

$$\left| \text{Methane} = \sum_{i=1}^{n} M \times L_o \times k \times e^{-k \times t_i} \right| \quad \textbf{(2)}$$

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[15] Gas Oxidized refers to the extent to which escaping methane is oxidized in a soil layer on top of the landfill.

[16] Debra Reinhart, *First Order Kinetic Gas Generation Model Parameters for Wet Landfills* (EPA-600/R-05/072, June 2005), at Part 2-6, which describes 12 different variations on the same form. The variants primarily modify the manner in which time is accounted for (e.g. delaying the onset of gas generation for a lag phase, using decimal time instead of annual time intervals, etc.), rather than making the model more robust by accounting for more factors. Current default values recommended by EPA, which were reached by trial and error, are L_o = 100 m^3/Mg and k= 0.04/yr. EPA, *AP-42: Municipal Solid Waste Landfills*, Vol. 1, , at p. 2.4-4.

Where: M is remaining mass, L_o is lifetime gas potential, k is annual decay rate

Unfortunately, this simplified model, and all of its variants, was derived from, and is only applicable to, a continuous decay phenomena acting upon a declining mass, where the decay rate is independent of the availability of limiting pre-conditions that otherwise would impede particle disintegration. An example would be the radioactive decay of a uranium isotope that is represented by a constant decay rate multiplied by the mass, which declines each year as the original mass is reduced by the prior year's decay.

Moisture pre-condition. Anaerobic decomposition in a landfill suffers far too many complications for such a simplified model to be valid. In particular, first, as discussed in this section, the model does not account for whether the distribution and quantity of essential moisture is adequate to sustain the near optimal levels of decomposition assumed by the model. Yet, inexplicably, the Draft's list of relevant factors for methane formation ignores the necessity for their being very high moisture levels.[17]

Along with heat, microbes and pH, which generally are not limiting conditions, decomposition in a landfill cannot comprehensively proceed as the model predicts unless there is a continuing adequate supply of moisture greater than 50%. However, the entrained moisture in the incoming wastes is less than 25%,[18] and the very act of collecting gas from a landfill quickly dehydrates a covered site in a few years because half of the gas removed (by weight) is water vapor.[19]

In addition, the liquids need to be evenly distributed. Unfortunately, moisture is not dispersed throughout landfills. Municipal solid waste is exceedingly heterogeneous, heavily compacted in a landfill to about eight times its original volume, interspersed over each day's lift with daily cover, and often confined in splayed open plastic bags, all of which creates highly preferential paths of flow. Earlier estimates from the 1990s are that liquids only reach 23% to 34% of the mass,[20] and, with in-place densities more than 50% greater today, the dispersion of moisture is presumably significantly less now.

Typically, then, and at best, only limited volumes of gas is actually generated at an operating landfill, before it is closed tight. Even for that short period, decomposition is essentially restricted to isolated pockets where there are aggregations of food scraps and grass clippings that transport their own moisture with them, as well as at the bottom where hydraulic heads accumulate above clogged leachate lines and gravel beds. Differences in cover and operational

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[17] Draft, at p. 2, lines 21-25.

[18] George Tchobanoglous, *Integrated Solid Waste Management: Engineering Principles and Management Issues* (McGraw-Hill, 1993), at pp. 72-73 and 393.

[19] Rapid dehydration can be seen by the fact that, at 100% saturation and 40° C (104°F) temperature, the condensate is 51% by weight of the weight of the gas, according to standard Humidity Tables, and landfill gas weighs 0.0834 lbs./cf., according to standard conversions.

[20] Debra Reinhart, *Prediction and Measurement of Leachate Head on Landfill Liners,* Florida Center for Solid and Hazardous Waste Management (Report #98-3) (1998), at p. viii.

practices implicate whether there is any replenishment or supplementation of moisture levels in situ that, in some cases, increases gas generation. After closure, and for as long as the cover seal maintains its integrity, gas generation rapidly tapers off as the site, for a time, takes on the intended characteristics of a "dry tomb." After the cover eventually fails, gas generation resumes until the residual carbon is exhausted and the site is biologically stabilized.

None of this wide moisture related variation in the rate of decomposition, and gas generation, is accounted for by FOD modeling, which represents a continuous function and that divergence underlies the irrational outputs the model generates.

Anomalous outputs. The extreme inexplicable and anomalous variability of the results the FOD model produces, which is widely reported in the literature, undermines its credibility at the outset. Even the EPA AP-42 background paper acknowledged that in its analysis:

> "The recommended defaults k and Lo for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH4 emissions that ranged from ~30 to 400% of measured values and had a relative standard deviation of 0.73."[21]

The most recent survey by Thompson of the results of FOD modeling in landfills concluded that:

> "Landfill gas models continue to receive criticism due to their poor accuracy and insufficient validation: most model results have not been evaluated against methane recovery data. A few studies have compared methane recovery data to estimates of methane generation from models, but only for a few landfills. This limited approach is inadequate to validate the model for a wide, rather than site-specific application."[22]

Similar:

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[21] EPA, *Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills* (EPA/600/R-08-116) (September 2008), at p. 9.

[22] Shirley Thompson, et al., "Building a better methane generation model: Validating models with methane recovery rates from 35 Canadian landfills," *Waste Management* 29 (2009), 2085, at 2086. Thus, to illustrate Dr. Thompson's point, the oft- cited French study, K. Spokas, et al., "Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems," *Waste Management* 26 (2006) 516, which was based on a study of only three landfills, was rejected by EPA's own consultant, who found:

> "The results of this study on two landfills reported LFG collection efficiencies of 94 percent and 98 percent. However, at the French facility that reported 94 percent LFG collection efficiency, this efficiency was based on the lowest of three predicted LFG generation levels for that facility. When the highest estimate of LFG generation is used, then the LFG collection efficiency drops to 84 percent. This raises the issue again that a major difficulty in determining LFG collection efficiencies is accurately estimating LFG generation levels." Memorandum to Brian Guzzone, US EPA, from Chad Leatherwood, Eastern Re search Group, Inc., dated November 18, 2002, re: Review of Available Data and Industry Contacts Re: Landfill Gas Collection Efficiency, at p. 2.

> "Results of this study suggest that the first order model cannot always be applied to full-scale landfill gas collection data with statistical significance."[23]

Another published paper that performed a random verification of related modeling of California landfills found a dispersion of 25 major landfills of predicted compared to actual values for gas collection efficiency, which ranged from 7% to 100%.[24]

A more recent unpublished survey of 46 California landfills by the California Air Resources Board reproduced in Table 1 found implied gas collection efficiency from gas generation estimated with LandGEM first order equations ranging from 6% to 225% gas captured, which is an exceedingly impressive engineering feat. California Air Resources Board, Staff Spreadsheet Titled Landfill Survey Data Public (2010), released in response to a Public Records request by Californians Against Waste. Similarly, the Wisconsin Department of Natural Resources did a comparison of actual gas collected to estimate gas generation in the State's landfills and found a wide and physically impossible outputs like those found in California's study. See on-line at http://dnr.wi.gov/org/aw/wm/solid/gas/gas.htm#art6.

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[23] Debra Reinhart, "Landfill Gas to Energy: Incentives and Benefits," University of Central Florida (Report #08-32026)(February 2010), at p. vi.

[24] Nickolas Themelis and Prisilla Ulloa, "Methane generation in landfills," *Renewable Energy* 32 (2007), 1243, at 1250.

Landfill Survey Response Data			Survey CH4 Captured/Model CH4 Generation (%)						
Landfill	**2006 WIP (%)**	**Avg. CH4 (%)**	***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***
1	9.4%	35%	109%	120%	107%	108%	112%	140%	140%
2	3.7%	46%	87%	108%	114%	109%	107%	135%	130%
3	3.2%	52%	61%	63%	73%	68%	52%	51%	83%
4	3.0%	39%	63%	73%	66%	79%	76%	90%	87%
5	2.7%	36%	91%	91%	91%	91%	84%	98%	92%
6	2.3%	34%	121%	121%	121%	121%	121%	121%	121%
7	2.2%	42%	99%	105%	109%	111%	105%	107%	104%
8	2.2%	14%	6%	5%	4%	6%	5%	6%	6%
9	1.9%	16%	66%	65%	65%	57%	59%	76%	76%
10	1.8%	25%	125%	113%	100%	97%	112%	124%	124%
11	1.8%	50%	64%	69%	71%	69%	66%	63%	63%
12	1.8%	42%	127%	127%	127%	127%	127%	146%	117%
13	1.4%	32%	121%	137%	128%	123%	119%	126%	126%
14	1.3%	49%	124%	119%	105%	102%	102%	76%	72%
15	1.3%	50%	59%	51%	41%	54%	54%	54%	54%
16	1.3%	43%	351%	261%	231%	226%	172%	166%	165%
17	1.2%	40%	45%	45%	45%	45%	53%	46%	44%
18	1.1%	39%	118%	118%	118%	118%	133%	118%	109%
19	1.1%	47%	78%	54%	96%	103%	90%	90%	116%
20	1.1%	44%	64%	63%	65%	40%	51%	39%	37%
21	0.8%	51%	89%	90%	103%	82%	81%	83%	108%
22	0.7%	50%	74%	73%	76%	88%	75%	94%	121%
23	0.6%	48%	152%	180%	140%	109%	104%	96%	91%
24	0.5%	48%	28%	35%	42%	50%	62%	70%	64%
25	0.4%	59%	57%	57%	57%	57%	57%	57%	57%
26	0.4%	29%	22%	22%	20%	21%	21%	25%	21%
27	0.4%	48%	23%	23%	23%	23%	15%	21%	34%
28	0.3%	38%	20%	26%	23%	21%	19%	14%	16%
29	0.3%	40%	111%	111%	116%	102%	114%	99%	98%
30	0.3%	43%	104%	104%	104%	104%	104%	93%	114%
31	0.3%	37%	29%	29%	29%	30%	33%	28%	25%
32	0.2%	42%	31%	31%	31%	31%	31%	28%	34%
33	0.2%	41%	22%	22%	19%	20%	21%	24%	30%
34	0.2%	48%	103%	85%	80%	91%	124%	123%	135%
35	0.2%	17%	6%	6%	5%	6%	6%	6%	6%
36	0.1%	48%	78%	78%	78%	102%	74%	66%	79%
37	0.1%	32%	35%	40%	38%	54%	62%	62%	50%
38	0.1%	33%	38%	17%	20%	16%	17%	27%	23%
39	0.1%	38%	257%	257%	341%	234%	234%	216%	257%
40	0.1%	37%	44%	38%	33%	18%	33%	33%	33%
41	0.0%	45%	76%	76%	76%	85%	78%	65%	76%
42	0.0%	37%	69%	66%	63%	59%	56%	52%	49%
43	0.0%	30%	46%	41%	37%	32%	27%	23%	19%
44	0.0%	27%	165%	161%	157%	138%	137%	138%	126%
45	0.0%	31%	38%	38%	38%	38%	38%	22%	47%
46	0.0%	30%	18%	17%	14%	14%	14%	14%	10%

Statistical validation failed. Initially, attempts to support the validity of FOD models was based upon a putative statistical test using regression equations of a sample that purported to show its predictions were a good fit.

The regression analysis prepared for EPA by Peer was intended to validate the FOD model's applicability to the approximately 2,000 MSW landfills in the United States,[25] but it failed to do so. The Peer study used too small a sample of only 21 landfills, or only 1% of the population, which is too few degrees of freedom for statistical significance. Also, none of those selected for the sample were chosen randomly, which removes the normal distribution essential for regression equations to estimate a population.

Furthermore, not only was the selection process not random, it was also chosen with a specific bias that has the effect of significantly skewing results to appear to show high capture rates. This was done by limiting the sample to landfills with energy recovery. These facilities typically recirculate leachate, which accelerates decomposition and gas generation,[26] in order to boost the profitability of electricity sales. That has been shown to increase near term gas generation very significantly, while only moderately increasing the volume of gas captured.[27] Since the model is blind to the fact that gas generation was augmented, the uptick in gas collected makes it seem appear that capture rates have significantly improved, even though they most probably have significantly declined.

Moreover, in addition to all those limitations, circular reasoning was used in performing the model's attempt at a statistical validation. In an attempt to assess the reasonableness of the model's estimates of Gas Generation, Eq. (3) is used to provide a putative independent estimate:[28]

$$\left| \mathit{Gas\ captured} = \mathit{Gas\ generated} \times \mathit{Gas\ capture\ rate} \right| \textbf{(3)}$$

Solving Eq. (3) for Gas Generated is shown in Eq. (4):

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[25] R. L. Peer, et al., "A comparison of methods for estimating global methane emissions from landfills," 26 CHEMOSPHERE 387 (1993).

[26] Debra Reinhart, *First Order Kinetic Gas Generation Model Parameters for Wet Landfills* (EPA-600/R-05/072)(June 2005), at p. 2-2.

[27] Contrast: Pat Sullivan and Alexander Stege, "An Evaluation of Air and Greenhouse Gas Emissions and Methane-Recovery Potential from Bioreactor Landfills," *MSW Management* (Sept./Oct. 2000), at p. 78, states that bioreactor landfills increase near term gas capture per ton of waste-in-place by 76%; with 67 FEDERAL REGISTER 36463 and 36465 (May 22, 2002), which states that bioreactors increase gas generation in the near term by 2 to 10 times.

[28] Debra Reinhart, "Landfill Gas to Energy: Incentives and Benefits," University of Central Florida (Report #08-32026)(February 2010), at p. 4.

$$\text{Gas generated} = \frac{\text{Gas captured}}{\text{Gas capture rate}} \qquad \textbf{(4)}$$

But, since only one of the two independent variables is known, this exercise rests on a house of cards. For the Gas Capture Rate is also unknown and an unsupported guesstimate is used, defeating the attempt to provide a solid foundation for the calculation. Thus, to solve the equation for Gas Generation, the study just *assumed* that Gas Capture Rate was 75% at all times during a landfill's life. Recalling that one of the purposes of the entire exercise was to establish a factual basis for assuming 75% capture rates in the first place, this led to a circular exercise with no statistical value. As a tautological statement, it establishes nothing about Gas Capture Rates anymore than it does about Gas Generation.

Moreover, the problem is not just that the provenance of the 75% assumption is neither an observed value nor, in view of its definition as the best systems during the limited period of their peak performance, even a reasonable assumption. In addition, in order to perform the Pearson calculations, the analysis assumed that every single landfill in the study (i) exhibited identical performance, even though operating practices significantly affecting collection efficiency vary widely among landfills, as well as (ii) achieved that same high capture rate during all phases of each sites' biologically active or latent life, including the challenging times when there is no installed or functioning gas collection system. However, US EPA has never asserted that its 75% assumption was intended to apply for each landfill at all times. Rather, to the contrary, it only purported that 75% was intended to be an average value when considered across peak times and among all landfills.[29]

Finally, in view of the fact that moisture, which is a limiting condition for decomposition landfill decay behavior obviously reflects complex interactions, which are especially difficult to model in a heterogeneous waste mass that goes through multiple phases some of which when prerequisite moisture levels are absent. The reason given to justify the paucity of other explanatory variables in the model to explain that complex environment, such as critical internal moisture levels, is that the excluded variables had statistically insignificant estimated coefficients in earlier versions of the regressions.

But, the problem of statistically insignificant coefficient estimates arises for many reasons other than the authors' claimed lack of importance. One of the reasons for insignificant coefficients is a small sample size that leads to limited degrees of freedom, which is evident in the study. Other problems include poorly formulated equations, data measurement errors, and inappropriate error term distribution specifications and related estimation procedures. Each of these problem s exist.

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[29] Debra Reinhart, *First Order Kinetic Gas Generation Model Parameters for Wet Landfills* (EPA-600/R-05/072, June 2005), at p. 3-2 and 5-2. US EPA, *Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills* (EPA/600/R-08-116) (September 2008), at p. 7-8.

This points towards an unreliable and questionable estimation process known as data mining or fishing, and not to the lack of importance of things, such as moisture, needed for a valid model. With these fishing procedures, various fuller models are formulated and discarded, not because they are not well formed or include inappropriate variables, but because the analysts did not want to confront the substantial complexities or consequences that more complete modeling would entail.

The exclusion of variables merely on the basis of low levels of estimated coefficient significance is not statistically justified, as dramatically shown by the irrational scattergun outputs it produces. For, if the excluded data are truly relevant, their exclusion leads to estimation bias and unreliable results. Coefficient significance is not an appropriate means for deleting variables from a regression model. Various appropriate tests exist for testing overall significance of a set of variables – in particular maximum likelihood ratio tests. The Peer paper does not show that these forms of significance testing were performed.

Due to all of the deficiencies discussed above, the results of the regression analyses cannot be relied upon to provide credible annual methane production quantities, anymore than the putative validation of the FOD model can corroborate that the model conforms to statistical norms. In addition to all of the problems discussed above, the low levels of R^2s in the Peer study (one measure of the explanatory power of estimated regression equations) do not support a conclusion that the regression analyses provide reliable results.

The reason why the FOD model's outputs are anomalous is that its coefficients, variables and structure are incomplete and its input variables are wrong.

The most recent attempt by Thompson to validate FOD models through modifying its architecture is similarly flawed.[30] Thompson searches for the best FOD model to validate for estimating gas generation in order to solve the mass balance equation. It uses the Pearson correlation to compare the modeled estimates of gas generation to what it construes to be observed values among six variants of the FOD model at 35 non-randomly selected Canadian landfills with alternative assumptions about one of the factors, namely the assimilated organic fraction in the landfill, and adjustments to the values for L_o and k that are irrelevant to gas generation.

The problems with this attempt are, first, that this so-called calibration approach is more akin to correlation fishing with a torn net. The study does not present a rational conceptual solution to errors that it identified in past modeling practices. Instead, by trial and error, it iteratively examines for each landfill the modeled gas generation estimates from each of the six variations on the same core equation, along with alternative input values, until it finds a best fitting Pearson correlations among historic landfill data.

However, the Pearson correlation does not show causality, but only a correlation that might be due to chance – a possible explanation whose probability increases markedly as the number of different values for variables and model permutations multiply, which more accurately

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[30] Shirley Thompson, et al., "Building a better methane generation model: Validating models with methane recovery rates from 35 Canadian landfills," *Waste Management* 29 (2009), at p. 2085.

resembles shooting fish in a barrel for correlates. In addition, the Pearson correlation is a process that says nothing about whether all critical explanatory variables, such as critical moisture levels, have been included in the model. As such, the Study's procedures are not a valid statistically appropriate procedure to derive reasonable estimates useful for future predictions of gas behavior among the population of municipal solid waste landfills.

Second, like Peer, the Thompson study is also circular. Pearson's correlation looks for linear associations between observed values and the parallel modeled estimates, here of gas generation. However, there are no observed values of gas generation to search for correlations with modeled generation outputs. In the three-term simplified mass balance equation above, only gas captured was known. In order to perform the Pearson analysis, the study resorts, at p. 2088, to the use of Eq. 4 to model further what is intended to be observed gas generation.

But, again, this equation with three terms, which is used in an effort to provide an observed value for gas generation, also has two unknowns. To produce a value for the desired observation for gas generation, the study is forced to make another assumption, which is not based upon any observations, about the gas capture rate. In this study, collection efficiency is *assumed* to be the average of 75%, which is the oft-cited US EPA assumption based upon the questionable decision to focus on the best systems at the limited time of their peak performance, and 85%, which is the claimed, but disputed, *Spokas* assumption,[31] or 80%. However, the EPA view is based upon a literature review that simply ignored low reported values in the published literature. As regards *Spokas*' claimed 85% value, as noted previously, it was even rejected by EPA and also by *Thompson*.

Again, too, like Peer there is the further problem that, in order to perform the Pearson calculations, the analysis assumed that every single landfill in the study (i) exhibited identical performance during all phases of each sites' life, which is something that EPA never claimed for the assumption.

By way of comparison, incidently, the Intergovernmental Panel on Climate Change (IPCC) states that the average lifetime capture rate equivalent to EPA's best instantaneous rate is actually as low as 20%.[32]

Thus, when the *Thompson* study rejected several scenarios because they seemed to "consistently produce[] much higher estimates than the [observed] methane generation rates," the calculated large standard errors it thought the analysis found were actually due to its arbitrary assumption about high capture rates rather than a real statistical deviation. Had the study used the lower IPCC assumption, the findings about which model showed the best fit would probably have been reversed.

As to the intention to improve upon the L_o and *k* values by localizing them to the conditions in the Province in which the landfill is located, those only create the illusion, but not

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[31] , Kurt Spokas, et al., "Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems," *Waste Management* 26 (2006), at p. 516.

[32] IPCC, *Fourth Assessment Report:* Chapter 10:Waste Management (2007), at p. 600.

the substance, of refinement. Using Provincial waste audits to derive L_o is a meaningless gesture because audits are just visual inspections with very wide and unknown bands of uncertainty no better than the three-fold dispersion, from 100 to 310 m^3/Mg., currently in the literature.[33]

Similarly, the attempts to refine the k value by more closely correlating it to the Province's annual precipitation is also meaningless because the relevant criteria is moisture *inside* the landfills at different points in a landfill's life, not rainfall *outside* the facility. Directly intervening between surface and interior conditions at any given time are the permeability of any cover, any re-injection of leachate or outside liquids, in-situ compaction ratios, waste composition, the functionality of the leachate collection system, site geometry and surface grading practices. At times, in fact, after the final cover is installed and for as long as it is maintained, the waste mass will go bone dry and therefore generate very little gas (hence the moniker, "dry tomb landfills"), even if there is a monsoon raging at the surface.

But, most important for the model's structure, those factors affecting interior moisture levels vary over time. To illustrate, there is no low permeable cover until 5 to 15 years after first waste emplacement (when significant gas is generated), and then a barrier to infiltration installed and remains for as long as the cover is maintained (when very little gas is generated), after which its performance will decline and rain will re-infiltrate the site (when gas generation resumes). Therefore, the operative decay rate is not the same in those three different phases.

If the model is to reflect the critical limiting conditions for decomposition to occur, such as internal moisture levels, then the value for *k* also must be appropriate, and different, for those distinct time periods. That would be higher in the first and the last phase and much lower in the middle phase of a landfill's biologically active or latent life. Slightly modifying the value for *k* by site location, rather than by the landfill's phase, and as a constant value under all of these conditions, fails to rectify the fundamental flaw in the first order decay model as it is presently constructed. The use of a constant k value, more closely tied to a largely irrelevant factor, fails to correct the flaws in FOD models current contemplation of *k*.

Data Problems. The underlying data for the analysis is not transparent, but, we continue to believe that the data inputs used for Gas Captured and Methane Destroyed, systematically understate not only Gas Generation for the reasons described above, but also Gas Captured and destroyed.

From past experience, we believe that the aggregated data for Gas Captured continues to be grossly inflated. In the past when we last consulted for EPA, the landfill owners and vendors refused to provide actual data on gas collected at each landfill for the purpose of compiling a national data base, even though this data is typically available buried in the files of state regulators. In lieu of actual data, the nameplate capacity of the permitted flares were multiplied by the number of hours. This fails to account for subpar performance, maintenance and unexpected downtime. States should be queried to compile actual data, or if that is not possible, a statistical sample of landfills should be selected and state records reviewed to estimate the deviation from manufacturers' claimed values for the different equipment.

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[33] Debra `, *First Order Kinetic Gas Generation Model Parameters for Wet Landfills* (EPA-600/R-05/072, June 2005), at p. 3-2.

On a related note, while the high methane destruction values used are appropriate for flares, state enforcement officials report seeing performance for internal combustion engines below 95%. Field data should be compiled from actual state reports to improve the reliability of long-held assumptions. It is unfortunate that AP-42 continues to fail to provide any of the data that it collected in a form from which more reliable estimates might be developed.

B. <u>First Three Phases.</u> As noted, decomposition, and gas generation, are not a continuous function but rather are moisture dependent. In turn, the level, and distribution, of moisture depends primarily upon when the final cover is installed, and whether leachate is recirculated (and/or outside liquids added), as well as waste composition, in-situ compaction ratios, precipitation and transpiration, the presence of active gas collection wells, and surface grading

Typically, after first waste emplacement, the gas collection system is not installed for five years in large landfills (though not in smaller ones), but it does not function to its design standards until the final cover is installed soon thereafter that creates a necessary seal for the system's vacuum forces to work properly and to prevent oxygen infiltration from the surface when it fully draws. Before the cover is installed, moisture is brought to the landfill entrained in food discards, grass clippings and left over liquids at the bottom of containers, which is supplemented by infiltrating rainfall while the top remains open while the cell fills up. Following capping, the residual moisture is quickly dehydrated by the gas systems, because half of the extracted gas by weigh is water vapor.

In wet cell landfills, discussed later, leachate is recirculated soon after first waste emplacement in order to accelerate decomposition, and often the final cover is delayed for several more years to extend the time when infiltrating rainfall can replenish moisture levels.

Thus, through the period of time that the cover is maintained, which may be approximately 30 years following closure, the landfill proceeds through three phases:

- 1 Pre-installation of the gas collection system
- 2 Post-gas collection installation but pre-installation of the final cover
- 3 Post-installation of the gas system and final cover but prior to the end of post-closure maintenance

This is not controversial. These different phases are accepted by EPA, and, indeed, the structure is reflected in the GHG Reporting Rule, and by the landfill industry.[34] These phases directly implicate how a landfill GHG inventory needs to be calculated. For, each of these phases evinces very different characteristics for the gas generation and gas collection, that varies significantly what is assumed in the First Order Decay model used in the draft inventory:

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[34] 40 C.F.R. §98.340 Subpart HH. US EPA, *Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills* (EPA/600/R-08-116) (September 2008), at p. 7-9; SCS Engineers (SCS), *Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills* (July 2007), at p. 10.

Three Phases of Landfill Life
Actual Landfill Characteristics Compared to First Order Decay Model

	Gas Generation	Gas Collection
Pre Gas Collection		
Dry Tomb	Same	Lower
Wet Cell	Higher	Lower
Post Gas/Pre Cover		
Dry Tomb	Same	Lower
Wet Cell	Higher	Lower
Post Cover-Pre Maintenance Ends	Lower	Higher

Comparing the second to the third column shows the point that Prof. Hans Oonk made to the draft version of AR4. It convinced the IPCC that the average lifetime capture rate that was equivalent to EPA's 75% assumption of what the best systems might achieve at the point of their peak performance is as low as 20%.

While the EPA and landfill industry have recognized the fact of these three phases of a landfill's life, they do not seem to appreciate the paradox that Oonk first raised, namely gas capture is only good when there is scant gas production, and when most gas is generated, there is little or no gas collection.

The draft inventory, however, recognizes neither, not the existence nor the phases or the paradox that they create. Indeed, by performing the first order decay model on total estimated landfill tonnages in each prior year, instead of on each individual landfill as a function of which phase it is in that year, the calculation ignores all of these very significant distinctions. In aggregate, the effect, again, is to grossly understate landfill GHG emissions.

C. Second Wave

To further complicate matters, there is a critical *fourth* time period in a landfill's life-cycle that is critical to include in the GHG inventory, yet is currently ignored in both the draft inventory and the GHG Reporting Rule. That is the second wave of gas generation, after postclosure maintenance ends, when the majority of a landfill's lifetime gases are generated, and, with the site abandoned, are released unabated.

Moisture restrictions. The second wave occurs because of three factors. First, as noted, the organic material in solid waste require 60% or more moisture to decompose, while incoming wastes contains less than 25% moisture. Absent additional liquids, decomposition will be minimized.

Distribution limited. Second, moisture is not evenly distributed in landfills. Solid waste is highly heterogeneous, heavily compacted to eight times its original density, inter-leafed with daily cover, and often confined in partially splayed open plastic bags, all of which combine to create highly constricted preferred paths of flow. Field studies, undertaken in the late 1990s when waste densities were only two-thirds of their current ultra-high compaction levels, show that entrained and infiltrating liquids only reach 23% to 34% of the mass.[35] With in-place densities today 50% to 66% greater than when the study was done, dispersion of liquids will tend to be significantly less.

Essentially, prior to the site closing and being covered with a low permeable liner, decomposition is confined to a few areas. It only occurs where there is moisture entrained with the incoming food scraps and grass clippings and leaking out the bottom of bottles containing fluids, as well as where rain travels through cracks and fissures and then pools in pockets where food is decomposing and in voids between large particles.[36]

After installation of the final cover, however, infiltration largely ceases and any residual moisture is quickly extracted with the gas, half of which is condensate (by weight) in the collection system, rapidly dehydrating the waste mass.[37] From the data, probably more than half of the original carbon content in the organic discards remains upon closure.[38]

Cover ultimately fails. Third, the final cover has a finite life. After closure, at best financial assurance regulations only provide funds for routine maintenance and for only 30 years.[39] As EPA repeatedly stated during the 1980's leading up to the promulgation of Subtitle D in 1991, even composite liners "will ultimately fail" within decades after the agency's post-closure care requirements have expired,[40] "and when they do, "leachate will migrate out of the facility."[41] Yet,

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[35] Debra Reinhart, *Prediction and Measurement of Leachate Head on Landfill Liners,* Florida Center for Solid and Hazardous Waste Management (Report #98-3) (1998), at p. viii.

[36] STI Engineering, *LFG Recovery* (Typescript, 2001).

[37] Rapid dehydration can be understand by the fact that, at 100% saturation and 40° C (104°F) temperature, the condensate is 51% by weight of the weight of the gas, according to standard Humidity Tables, and landfill gas weighs 0.0834 lbs./cf., according to standard conversions. Simplified gas generation rates are.10 cf per pound of MSW, declining 2%-3% per year. EPA, *Turning a Liability Into an Asset* (EPA 430-B-96-0004)(September 1996), at p. 2-5. At that rate, the landfill will become bone dry in approximately 3 years after new infiltration is blocked by the installation of a final cover and continuing through the time the cover is maintained.

[38] The best data, as we have repeatedly requested EPA to undertake, would be statistical bore samples after closure to measure unsequestered carbon content. However, this has never been done, notwithstanding the enormous importance the answer holds for the long term safety of landfills. For current financial assurances are only required for 30 years after closure.

[39] 40 C.F.R. §258.72.

[40] 53 FEDERAL REGISTER. 168, at pp. 33344-33345 (August 30, 1988).

[41] 46 FEDERAL REGISTER 11128-11129 (February 5, 1981). Similar: "A liner is a barrier technology that prevents or greatly restricts migration of liquids into the ground. No liner, however, can keep all liquids out of the ground for all time. Eventually liners will either degrade, tear, or crack and will allow liquids to migrate out of the unit. Some have argued that liners are devices that provide a perpetual seal against any migration from a waste management unit. EPA has concluded that the more reasonable assumption, based on what is known about the pressures placed on liners over time, is that any liner will begin to leak eventually." FEDERAL REGISTER (July 26, 1982), at pp. 32284-32285.

the EPA recognized, the duration of a landfill's hazardous loadings that needs to be isolated may be "many thousands of years,"[42] long after the time when discharges will occur.

The early warnings from EPA were more recently reinforced from an investigation and field study conducted by the agency's Inspector General –

> "EPA officials have stated that based on current data and scientific prediction, the release of contaminants may eventually occur, even with the application of best available land disposal technology. There is concern that *these barriers will merely postpone the inevitable release of contaminants until after the 30-year liability has expired*. As previously stated, some sites contain materials which are highly resistant to decomposition or which remain toxic forever. There have been several studies to determine the expected life span of landfill liners, and opinions on this issue vary widely. The bottom line is that not even the manufacturers claim that their liners will last forever."[43]

Why, then, did the EPA proceed to adopt liner-based regulations in 1991, when they were fully informed that engineered barriers will eventually fail? That question was answered by the EPA Inspector General a decade later in 2001. Extensive interviews with the agency's staff established that *the reason was political*, not technical–

"Landfill design requirements and post-closure maintenance for both Subtitle C and Subtitle D facilities are expected to prevent leakage in the short term; however, their long-term effectiveness in controlling releases of contaminants is unknown. EPA and others have stated that it is likely that some disposal facilities will leak at some period after they close. ... "However, some who commented were concerned that an extended time frame would place an economic burden on smaller businesses. Therefore, EPA officials *acknowledge the lack of criteria or scientific basis* for establishing the 30-year post-closure time frame. ... EPA made the decision to establish the time frame at 30 years, seemingly *based on a compromise of these competing interests*. EPA officials we spoke to agreed that the 30-year time frame was *not based on specific scientific criteria or research studies*."[44]

State environmental agencies reached the same conclusion about the fact that the covers would eventually fail and lead to a second wave of gas generation after maintenance ends at closed landfills. The California Integrated Waste Management Board stated:

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[42] 46 FEDERAL REGISTER 28314-28328 (May 26, 1981). *See, also*, Commission of the European Community*, Management and Composition of Leachate from Landfills: Final Report* (1994), at p. 7, TABLE 1.2. H. Belevi and P. Baccini, "Long Term Behavior of Municipal Solid Waste Landfills," *Waste Management and Research* (1989), at p. 43. Peter Flyhammar, *The Release of Heavy Metals in Stabilized MSW by Oxidation* (Swedish Department of Water Resources, Nov '99), at p. 20 TABLE 10.

[43] Office of the Inspector General, *RCRA Financial Assurance for Closure and Post-Closure* (2001-P-007) (Mar. 30, 2001), at pp. 33. On-line at: http://www.epa.gov/oigearth/audit/list301/finalreport330.pdf. (Emphasis added.)

[44] U.S. Environmental Protection Agency Inspector General, *RCRA: RCRA Financial Assurance for Closure and Post-Closure* (No. 2001-P-007) (March 28, 2001), at p. 31 (emphasis added).

> “However, the initial term of 30 years for P[ost] C[losure] M[aintenance] is unlikely to resolve all the environmental issues related to a closed landfill in California. Since Subtitle D was promulgated, research shows that certain wastes in some landfills stabilize in a short period of time and that, at those landfills, the potential to impact the environment may only last for a short portion of the conventional 30-year PCM period. On the other hand, some landfills may remain a threat to the environment for longer than 30 years. For example, stakeholders have reported to Board staff that landfill gas control systems have had to be installed at landfills that had not operated for up to 60 years. Dry tomb landfills (favored by Subtitle D and 27 CCR) indefinitely suspend and/or retard the decomposition process such that a breach in containment (e.g. extreme climate or earthquake event or inappropriate land use, or simply failure of equipment or containment barriers) could trigger uncontrolled production and release of landfill gas and leachate, and public contact with waste. *The state of the science thus indicates that municipal solid waste landfills will in many cases pose a significant threat to the environment well beyond the conventional 30-year PCM period*.”[45] (See accompanying FIGURE showing a second wave of gas generation denoted as “containment failure.”)

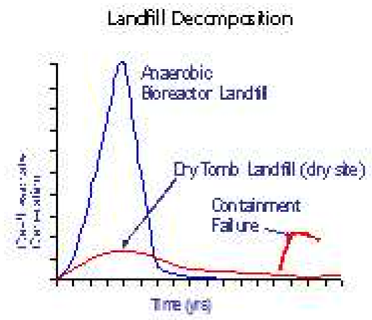

FIGURE 1

Similarly, Washington state’s Department of Ecology has stated:

“The extent to which today’s landfills adequately protect human health and the environment is a subject of debate, however. Requirements that govern siting, operation, closure, and post-closure are stringent and extensive. While the newest landfills are state-of-the-art facilities, they are far from benign in their impacts. Landfills may still affect the air, land, and water but to a significantly lesser degree than before today’s standards went into effect. As waste decomposes in landfills, methane and other hazardous gases are generated. Methane is a greenhouse gas concern because its impact is twenty-three times that of carbon dioxide (EIA). Leachate from decomposing matter in landfills can contain hazardous constituents. If landfill liners and/or leachate collections systems fail, then groundwater and surface-water pollution can occur. No liners are engineered to be 100 percent impenetrable or to last forever without some sort of failure. In fact, US EPA officials have stated that problems can occur more than thirty years after closure of

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[45] CIWMB, Discussion Paper Regarding Postclosure Maintenance Beyond the Initial 30 Years and Financial Assurance Demonstrations (December 6, 2004) (emphasis added).

> a landfill, pointing out that 'even the best liner and leachate collection system will ultimately fail due to natural deterioration.'"[46]

In addition, the Wisconsin Department of Natural Resources has also pointed to the same inherent flaw in dry tomb designs for landfills:

> "The problem with dry tomb landfills is that the organic wastes in them remain largely undecomposed. They represent a continuing and large potential source of methane gas, as well as a potential source of groundwater pollutants. The essentially perpetual management of these problems represents a long-term financial liability to the waste management industry, and potentially to the state, if public monies have to be used to clean up future problems."[47]

Furthermore, in the last three years, many in the landfill industry have conceded these basic facts, as well. The Executive Director of the Solid Waste Association of North America (SWANA), John Skinner previously headed EPA's Office of Solid Waste where he had a major role in drafting Subtitle D. Dr. Skinner has recently written:

> "The problem with the dry-tomb approach to landfill design is that it leaves the waste in an active state for a very long period of time. If in the future there is a breach in the cap or a break in the liner and liquids enter the landfill, degradation would start and leachate and gas would be generated. Therefore, dry-tomb landfills need to be monitored and maintained for very long periods of time (some say perpetually), and someone needs to be responsible for stepping in and taking corrective action when a problem is detected. The federal Subtitle D rules require only 30 years of post-closure monitoring by the landfill operator, however, and do not require the operator to set aside funds for future corrective action. Given the many difficulties of ensuring and funding perpetual care by the landfill operator, the responsibility of responding to long-term problems at dry-tomb landfills will fall on future generations, and the funding requirements could quite likely fall on state and local governments."[48]

Dr. Skinner's predecessor at SWANA, Lanier Hickmanexpressed the same view more forcefully:

> "Currently many policymakers view F[inancial] A[ssurance] for landfills from the perspective, 'If it ain't broke, don't fix it.' However, *the question is not 'if' there will be future landfill problems, but 'when.'* Since FA requirements are the last

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[46] Washington Department of Environmental Protection, *Background Information for Beyond Waste Document* (2004), at p. 3.

[47] Testimony of Suzanne Bangert, Director Wisconsin Department of Natural Resources Bureau of Waste Management Before the Assembly Committee on Natural Resources on Clearing House Rule 04-077 (April 27, 2005).

[48] John Skinner, "Composting and Bioreactors," *MSW Management* (July/August 2001), at p. 16 (emphasis added).

> line of defense before the public winds up with the costs for corrective action, it is critical that an FA mechanism be able to guarantee coverage of expected landfill costs."[49]

Or from Peter While, an environmental scientist with Procter & Gamble –

> "...The dry containment method of operating a landfill has been described as long-term storage of waste rather than waste treatment or waste disposal, and does have some significant drawbacks. There will always be pockets of moisture within waste, and *it is generally accepted that all lining and capping systems will eventually leak so rain and/or groundwater will eventually enter the site*. Thus, the decomposition of the organic fraction of the waste will eventually occur, with resulting emissions of landfill gas and leachate. Since pipes and pumps buried within the waste eventually clog up and fail, there will be less chance of collecting and treating these emissions if they occur in the distant future."[50]

Or from John Pacey, one of the premier landfill engineers –

> "The containment provided by these landfills offers environmental protection initially; however, at some point *beyond the 30-year [postclosure] period, there may be partial failure(s)* of the containment lining system (underlying and overlying the waste). The primary environmental issue associated with partial containment system failure and moisture infiltration is the potential associated increase in gas and leachate production and the resulting impact of uncontrolled leachate and/or landfill gas releases to the environment. The nature and magnitude of the releases exiting the landfill and their resulting impacts are directly related to the amounts of organic waste not yet decomposed."[51]

Thus, a very substantial fraction and quite possibly a significant majority of the carbon in the incoming wastes remains when the landfill is closed due to insufficient and unevenly distributed moisture while open. Also, eventually the cover will fail after maintenance ends, reigniting a second wave of gas generation that will probably be larger than the first wave. At that time, there will be no gas collection and all of the future gases from the residual decomposables will escape into the atmosphere.

Not only is it vital that the fifth phase of a landfill's life be acknowledged, but also it is necessary to include the future emissions that will flow from today's discards in the annual GHG inventories. Yet, for the organic discards buried in the year for which the inventory is prepared, EPA's current practice purports to track each landfill's actual performance only in that annum.

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[49] Rob Arner, H. Lanier Hickman and Cristine Leavitt, "Dump Now, Pay Later?" *MSW Management* (Sept. 2000).

[50] Peter White, *Integrated Solid Waste Management: A Lifecycle Inventory* (Aspen Pub. 1999), at p. 275.

[51] John Pacey, *et. al.*, *The Bioreactor Landfill - An Innovation in Solid Waste Management*, Monograph (2001), at p. 2 (emphasis added).

However, in fact, we understand that the agency does not even recognize the fact that a not insignificant fraction of the gases generated that year are from open or not fully closed cells where there is either no gas collection or no low permeable cover. In those cells, the Gas Capture Rate is zero or a fraction of collection system's peak performance, while EPA's calculations presumes capture rates are a constant and optimal at all times, belying any claim that it is tracking each landfill's behavior in that year.

Even if the new four-phase protocols included in Table HH-3 of the GHG Mandatory Reporting Rule were followed in the inventory – which we do not believe it was – that would still ignore the fifth phase when, most likely, a majority of the gases are generated and, since none of those are captured, most of the fugitive emissions occur.

Accounting for future emissions. EPA has previously defended the inventory's omission of the vast majority of postponed GHGs that arising from the residual carbon in the wastes buried today. It has argued that the inventory only encompasses emissions estimated to occur in that year.

However, this view produces a result that ignores the majority of the delayed emissions associated with wastes deposited in that year, which, under EPA's protocols will *never* be counted for in the relevant future. This result is akin to assessing a person's dose absorption of a 24-hour time release pill in the first hour after its being swallowed, and ignoring the further uptake in the following 23 hours.

Moreover, EPA's opinion is fundamentally inconsistent with the IPCC principles that the agency has itself restated in its reports:

> "CH_4 emissions from landfills *are* counted [under the IPCC guidance in inventories of anthropogenic GHG emissions.] Even though the source of carbon is primarily biogenic, CH_4 would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH_4 formation. Note that this approach *does not distinguish between the timing of CO_2 emissions,* provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO_2, *it does not matter whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor).*"[52]

Finally, the refusal to acknowledge the future stream of methane emissions that inevitably will follow from the burial of organic discards today is also in fundamental conflict with other practices used elsewhere in the inventory. In order to compute the equivalent warming effects of other greenhouse gases to CO_2, each of which has different residence times, the accepted convention uses an assumed common 100-year period for the time each gas, released today, will remain in the atmosphere before it decays or is absorbed. Since methane actually only remains in

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[52] EPA, *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* (3rd Ed., 2006), at p. 12 (emphasis added).

the atmosphere for 12 of those 100 years, its actual impacts are diluted by being spread over 88 years when it is no longer present.[53]

In the event EPA's decision is to bar recognition for those delayed impacts, then, to be consistent, the protocols also must use a single-year basis for calculating the different gases' warming potential, something that would increase methane's carbon-equivalence by more than 100 times. But, the protocols cannot responsibly use a century long frame of reference in one chapter and an instantaneous snapshot in another and produce a coherent analysis in the conclusion.

As to the complaint that there is no nomenclature to properly account for the future stream of emissions in the inventory for the current year, there is a well-trod analogous mechanism to do this. Accounting routinely incorporates into the present a future stream of income flows that derive from an investment made today to best pick from various options. This directly resembles continuing gas emissions from decaying wastes discarded in that year. That technique is the net present value analysis, long used in economic planning and decision-making.

As to the complaint that present value type of calculations require making projections about future events that are not precisely known, that, too, is a red herring. For one thing, the current present-only analysis is already replete with made up assumptions without any factual basis, such as the gas capture rate. For another, ignoring future consequences that will follow from today's actions does not eliminate uncertainty. To the contrary, ignoring the future is a palpable decision that there will be no future decomposition activity from today's discards, which is a totally absurd result. Tomorrow's uncertainty cannot be eliminate by pretending it does not exist.

Of note, a present-value type of calculation attributing future emissions from wastes buried today to the current year is a practice that the IPCC has used elsewhere. The estimation technique of compressing into the present the future emissions from today's sources has more recently been specified as the appropriate methodology in the IPCC's Clean Development Mechanism program.[54]

E. Oxidation

The draft inventory continues the practice of continuing to assume that 10% of escaping methane is oxidized in the cover soil. Previously, EPA has effectively rested its case on the

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[53] IPCC, *Fourth Assessment Report*: Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing (2007), at p. 212, Table 2.14.

[54] IPCC, Proposed New Methodology: Baseline (CDM-NMB) Version 02 (July 15, 2005). As other examples, *see, also*, German Ministry for the Environment, *Waste Sector's Contribution to Climate Protection* (Research Report 205-33-314)(2006), at p. 15.

Czepiel study, which found in field and laboratory studies during 1994 that 10% of the methane generated in a landfill was oxidized in the cover soil over the course of a year.[55]

When the gases that are emitted are diffused throughout the overlying soil blanket, as would have been the case with most landfills constructed before 1991, this study would be applicable. However, modern landfills gases are not diffused at the surface throughout that earthen layer, because, since 1991 a composite cap has been required under that soil blanket, including in practice a 60-mil (or $^1/_{16}$") high density polyethylene plastic membrane that effectively impedes the passage of gases from the waste into that cover soil.[56]

This is key. It means that instead of the methane diffusing throughout the topsoil for maximum oxidizing effect, the gases that are released above the landfill are concentrated in high fluxes at a handful of cracks and tears in the plastic sheet. Concentrated high flux emissions quickly overwhelm the capacity of the topsoil to oxidize the escaping methane through these hot spots.[57]

Czepiel expressly stated that not only was his study not done at a landfill with a synthetic geomembrane, but also, "[p]eriodic maintenance of the cover materials has minimized significant surface cracks" in the clay layer, as well.[58] That is to say, nothing in his study can be used to describe what happens to the methane that flashes through a small number of hot spots on the top face of the landfill.

He further reemphasized again in his conclusion that his findings did not apply when gases are released in high fluxes through narrow cracks:

> "Waste settlement, surface erosion and soil dessication often promote significant surface cracking, providing paths of minimal resistance to gas flow, effectively bypassing microbial influence. Our study generally lacked surface cracks, although his characteristic may not be representative of the entire spectrum of landfill surfaces."[59]

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[55] Czepiel, *supra,* at p. 16,721. There are two other studies listed in the draft paper. However, the one by J. Jensen et al., "CH4 Emissions from Solid Waste Disposal," *Background Papers-IPCC Expert Meetings on Good Practice Guidance* (IPCC, 2002), is not a study but a proposed protocol for estimating methane emissions from landfills. In any event, Jensen acknowledges that "[t]he oxidation effect is also highly dependent on the type and thickness of cover at the SWDS." *Id.,* at p. 429 The other by Mancinelli was withdrawn upon our inquiry. The Mancinelli study has been withdrawn because a copy of the paper cannot be located.

[56] 40 C.F.R. §258.60(a)(1). As noted previously (see NOTE 111 on page 74), technically, the rule only requires that the permeability of the cover not be less than the bottom liner, although in practice this is met with a composite system in the cover as well.

[57] Czepiel, *supra*, at p. 16,727. Oxidation was observed to follow the Arrhenius relationship, or parabolic behavior, in which oxidation increases with greater inputs, but only to a distinct maximum, after which it rapidly declines.

[58] Czepiel, *supra,* at p. 16,721.

[59] Czepiel, *supra,* at p. 16,728.

Furthermore, a consultant for the U.K. Department on the Environmental conducted a comprehensive study involving 250 measurements at a landfill with a composite cover and found that there was no oxidation effect:

> "Methane oxidation is only observed where the diffusion gradient through the cap is very small, and therefore the methane oxidizing bacteria can cope with the rate of supply of gas. When higher fluxes predominate there is little evidence either for or against methane oxidation being a significant component of emission control."[60]

A similar field examination by researchers at a Swedish landfill corroborated the U.K. findings.

Other Technical Constraints on Oxidation

Even if, for the sake of argument, methane oxidation were able to occur landfills with plastic liners, there are many other limitations of Czepiel's findings when attempting to apply them without limitation to the typical landfill and across time.

For one thing, in northern climates, oxidation is improbable during cold winters. Also, in addition to the small cracks in the geomembrane, similar problems can afflict the clay liner as well. In the northern climatic zones, the freeze/thaw cycle is a constant source of cracking, and in hot, arid climates, clay is susceptible to cracking from dessication.[61] For another, remembering that landfill gas is heavier than air and seeks the path of least resistence, no one has yet been able to satisfactorily determine what proportion of landfill gases escape through the top of the landfill– where any oxidation that occurs would take place – and, through the bottom and even the sides of the site or through the leachate collection system – where it would not, as EPA has previously pointed out.[62] Then, too, there is the practical complications of maintaining optimized laboratory conditions for methanotrophs to oxidize methane over the long term at a real site.[63]

In any case, even if for the sake of argument it were considered appropriate to give the benefit of oxidation for the period of time prior to the installation of the final cover when there emissions might diffuse through any soil layer, EPA itself has stated that a concomitant reduction in collection efficiency would have to be registered to account for the lack of a seal necessary for efficient gas collection.[64]

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[60] AEA Technology, *Methane emissions from UK landfills* (UK Department of the Environment, Transport and the Regions, 1999), at p. 2-9.

[61] P. Lechner, C. Heiss-Ziegler and M.H. Humer, "Reducing Greenhouse Gas Emissions: How Composting and Compost Can Optimize Landfilling," *BioCycle* (September 2002).

[62] 56 FEDERAL REGISTER 24492 (May 30, 1991).

[63] Kightley, *supra*, at pp. 596 - 600.

[64] Debra Reinhart, *First Order Kinetic Gas Generation Model Parameters for Wet Landfills* (EPA-600/R-05/072, June 2005), at p. 5-2.

●

For the foregoing reasons, it is no longer rational or responsible to continue conducting the waste section of the GHG inventory exactly as it has done so in the past only because it has always done it this way, regardless of the fact that its foundations have been vitiated by the EPA's reports.

With kinetics experts as part of a team, we stand ready to accept a commission to revise the present first order decay model to properly reflect the things that we know make its present formulation useless.

Sincerely,

CENTER for a COMPETITIVE WASTE INDUSTRY

Peter Anderson

By:______________________________________
PETER ANDERSON
Executive Director

Appendix H

CITY OF OAKLAND

250 Frank H. Ogawa Plaza, Suite 5301 OAKLAND, CALIFORNIA 94612-2034

Public Works Agency
Environmental Services Division

FAX (510) 238-7286
TDD (510) 238-3254

April 14, 2010

Mr. Leif Hockstad
Environmental Protection Agency
Climate Change Division (6207J)
1200 Pennsylvania Ave., NW
Washington, DC 20460

RE: City of Oakland Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008 (March 2010)

Dear Mr. Hockstad:

The City of Oakland commends the U.S. EPA on continuing to track and report on U.S. greenhouse gas (GHG) emissions. We appreciate this opportunity to comment on the Draft Inventory of U.S. GHG Emissions and Sinks (Draft Inventory).

Recommendation: Include a "systems" or "consumption"-based perspective on GHG emissions within the Draft Inventory.

It is critical that we work together at all levels of government to track and report on GHG emissions in a manner that compels us to take action where we have opportunities for reduction. Framing GHG emissions in a "systems-based" or "consumption-based" view, in addition to the conventional "sector-based" view used in the current Draft Inventory, is important.

The EPA promoted this approach in its recent 2009 whitepaper "Opportunities to Reduce Greenhouse gas Emissions through Materials and Land Management Practices." The whitepaper, issued by the Office of Solid Waste and Emergency Response, presents an alternative "systems-based" perspective of GHG emissions that includes the upstream impacts of waste reduction and recycling. We find this framing equally compelling as the "sector-based" view. Each perspective has pros and cons, and each includes some data the other ignores when evaluating a nation (or community) in isolation. Most importantly, each also informs consideration of GHG reduction opportunities that the other is not set up to recognize or encourage.

We need to achieve dramatic reductions in GHG emissions, which requires that we unlock new ways of reducing our collective carbon footprint. How we tell the story of our nation's carbon footprint can help to educate and motivate the individuals, communities, and organizations that our nation comprises to act on their own opportunities to reduce GHG emissions.

Waste reduction and recycling create clear GHG reduction benefits up and down the product lifecycle chain. Our national GHG story, told through the Draft Inventory report, should be framed to cause reflection and motivate action on these GHG reduction opportunities.

Our own staff analysis has shown that GHG reductions associated with waste reduction and recycling opportunities are on the same order of magnitude as those associated with the transportation and building energy use sectors. It is important that we take action in all three of these areas. The fact that they can't all be added and depicted in one pie chart should not prevent us from telling the story of their respective importance.

The simplest solution is to include both the "sector-based" and "systems-based" perspectives in the national GHG inventory. We plan to show both perspectives in our own local GHG accounting and reporting, and are encouraging all communities to make this standard practice. This relatively small adjustment to our reporting can have a big impact in creating GHG reductions associated with lifecycle impacts of all the things we purchase, use and discard.

Please feel free to contact Garrett Fitzgerald, the City of Oakland's Sustainability Coordinator, at gfitzgerald@oaklandnet.com or (510) 238-6179 if you would like to further discuss any of these comments.

We look forward to working with you, the U.S. EPA, and other government agencies as we collaborate to reduce GHG emissions in a meaningful way.

Sincerely,

Susan Kattchee
Environmental Services Manager
City of Oakland

Appendix I

Appendix I

Citizens' Environmental Coalition

Main Office: 33 Central Ave, 3^{rd} Floor, Albany, New York 12210
Phone: (518) 462-5527 ◆ Fax: (518) 465-8349 ◆ E-mail: *cectoxic@igc.org*

Websites: www.cectoxic.org ◆ www.ecothreatny.org ◆
www.toxicfreefuture.org

April 13, 2010

Mr. Leif Hockstad
Environmental Protection Agency
Climate Change Division (6207J)
1200 Pennsylvania Ave., NW
Washington, DC 20460
Also sent by email to hockstad.leif@epa.gov

Re: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008

Dear Mr. Hockstad,

We are writing to address some of the inadequacies of the national Greenhouse Gas Inventory and to make specific recommendations for more timely amendments to reflect better science and for improvements to better identify more sustainable options that achieve greenhouse gas reductions. We particularly focus on the inadequate accounting for waste and wasting in the inventory. We have actively engaged in New York's state level greenhouse gas inventory and are concerned that EPA's inventory will hurt our efforts to obtain better scientific treatment of waste issues.

- As currently structured the national inventory gathers rough estimates of end of the pipe emissions of greenhouse gas emissions.
- To a great extent the inventory looks at historical information.
- The national inventory uses conventions adopted for the 2nd IPCC assessment. As a result newer, better information since that time are not being incorporated into the national greenhouse gas inventory.
- The categories of emissions primarily relate to extremely large sectors of combustion sources-- power plants, mobile sources, heating of buildings, etc. The accuracy of these emissions estimates is limited by the methodology and the broad economy- wide focus.
- Despite such problems numerous entities, public and private are engaged in this data collection devoting significant time, energy and personnel resources to the effort.
- There is a massive task before us: achieving 80% reduction in greenhouse gas emissions by 2050 nationally and also globally. Unfortunately, the national inventory is so broad that it is really not useful in identifying the solutions we desperately need immediately.

We recommend amendments to the national inventory and that EPA:

1. Seek global agreement to update the methodology so that it reflects the best current scientific information.
2. Continue to use the agreed upon 2nd IPCC assessment guidance, but add a supplement to the inventory that reflects current understanding of better scientific information. This also will help identify additional opportunities for greenhouse gas reductions. For example, see our discussion of issues related to WASTE below.
3. Identify solutions and best practices which can be implemented immediately by state and local governments. All solutions and best practices should be sustainable, offering benefits in 3 spheres -economic, environmental and social-- with no damaging or detrimental drawbacks. Adopting sustainable solutions becomes easy, when multiple benefits, beyond GHG reductions, are within reach .
4. Do more analysis at the micro-level. What is the most efficient way to get food from the farm to household dinner tables? the most efficient way to deliver health care? How energy efficient can supermarkets be made? Hospitals? Sewage treatment plants? Schools? Various industries? Etc.
5. Strive to make all of the systems we use and rely on - sustainable. Until we do we will not be able to address climate change.
6. Immediately address WASTE and WASTING in a much more substantial way. Post World War II we have dramatically increased the amount of waste we generate. WASTE and WASTING are similar to energy losses, except that waste involves the loss or destruction of material resources as well as embedded energy.

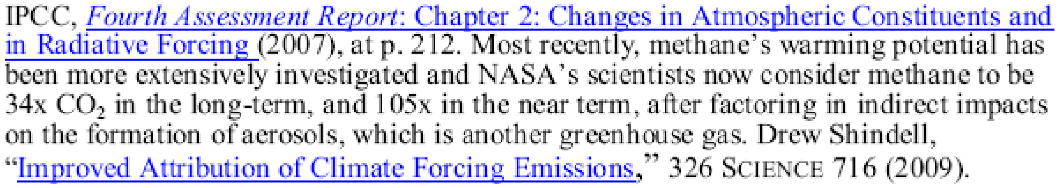
Waste

Waste involves a huge sector of our economy that is not adequately captured in the greenhouse gas inventory. This was illustrated for us recently as we worked on NY Climate Action Plan. New Jersey calculated much greater lifecycle emissions vs. direct emissions for waste management. The failure to include upstream GHG emissions and embodied energy in materials serves to disadvantage the most sustainable solid waste options (recycling and composting) vs. the most unsustainable solid waste options (incineration). Doing so flies in the face of EPA's WARM model which finds recycling to save 4-5 times the energy an incinerator recovers from waste. Waste and Energy Loss have many things in common and as a result no inventory can be considered adequate that gives little attention to waste.

We were also shocked to not see reference to EPA's recent report that put greenhouse gas emissions associated with non-food products and packaging at 37%, *EPA, Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices*, Sept. 2009. Joshuah Stolaroff, PhD worked on the EPA report and subsequently extended the analysis to include products produced abroad and consumed in the US. This Product Policy Institute white paper states total GHG emissions of non-food products and packaging is 44%. Both reports can be accessed at www.productpolicy.org Such information tells us that we are not appropriately accounting for the greenhouse gas impacts of waste. EPA's own WasteWise program has numerous examples of large corporations saving millions of dollars by reducing, reusing and recycling waste at their facilities. The dollars saved relate to less waste sent for disposal, less water use, less energy use, more efficient use of materials,etc. We have also included a factsheet we have prepared: *Waste Impacts Climate Change.*

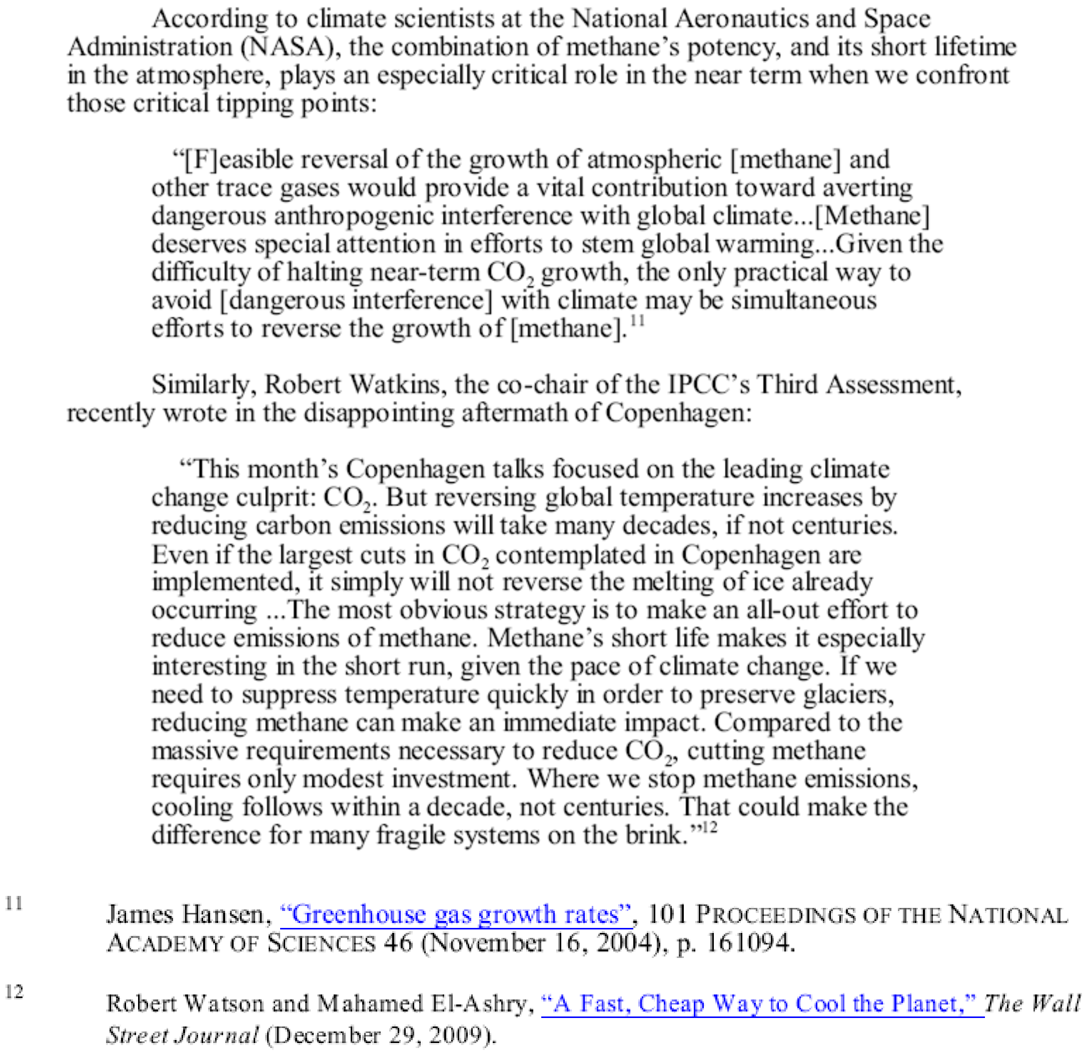
Methane

Global Warming Potential for Methane is listed as 21. We don't know the reason for using the 2nd IPCC assessment guidance for assembling the inventory rather than the 4th. However, methane is pretty unique and needs to have special consideration. It has now been recognized that methane has a relatively short life span in the atmosphere compared to CO2. It also has much greater global warming potential. Because of its shorter life, its global warming potential should be considered over 10 or 20 years, rather than 100 years. The 4th IPCC assessment puts the global warming potential at 72 over a 20 yr. period. A subsequent report from NASA puts the GWP at 34x CO2 for the long term and 105x in the near term because of its contribution to ozone formation.



IPCC, *Fourth Assessment Report*: Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing (2007), at p. 212. Most recently, methane's warming potential has been more extensively investigated and NASA's scientists now consider methane to be 34x CO_2 in the long-term, and 105x in the near term, after factoring in indirect impacts on the formation of aerosols, which is another greenhouse gas. Drew Shindell, "Improved Attribution of Climate Forcing Emissions," 326 SCIENCE 716 (2009).

There are important reasons to consider a shorter time frame for climate change. If we can adequately tackle significant greenhouse gases in the short term we might be able to avoid or delay the tipping point for a runaway situation. Doing so would give us more time to institute other more complicated measures to control CO2. Methane can be key to these short term measures.



According to climate scientists at the National Aeronautics and Space Administration (NASA), the combination of methane's potency, and its short lifetime in the atmosphere, plays an especially critical role in the near term when we confront those critical tipping points:

> "[F]easible reversal of the growth of atmospheric [methane] and other trace gases would provide a vital contribution toward averting dangerous anthropogenic interference with global climate...[Methane] deserves special attention in efforts to stem global warming...Given the difficulty of halting near-term CO_2 growth, the only practical way to avoid [dangerous interference] with climate may be simultaneous efforts to reverse the growth of [methane].[11]

Similarly, Robert Watkins, the co-chair of the IPCC's Third Assessment, recently wrote in the disappointing aftermath of Copenhagen:

> "This month's Copenhagen talks focused on the leading climate change culprit: CO_2. But reversing global temperature increases by reducing carbon emissions will take many decades, if not centuries. Even if the largest cuts in CO_2 contemplated in Copenhagen are implemented, it simply will not reverse the melting of ice already occurring ...The most obvious strategy is to make an all-out effort to reduce emissions of methane. Methane's short life makes it especially interesting in the short run, given the pace of climate change. If we need to suppress temperature quickly in order to preserve glaciers, reducing methane can make an immediate impact. Compared to the massive requirements necessary to reduce CO_2, cutting methane requires only modest investment. Where we stop methane emissions, cooling follows within a decade, not centuries. That could make the difference for many fragile systems on the brink."[12]

[11] James Hansen, "Greenhouse gas growth rates", 101 PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES 46 (November 16, 2004), p. 161094.

[12] Robert Watson and Mahamed El-Ashry, "A Fast, Cheap Way to Cool the Planet," *The Wall Street Journal* (December 29, 2009).

The Above References are from *Beyond Recycling: Composting*, by the Center for a Competitive Waste Industry, prepared for EPA, Region 9 by Peter Anderson, Gary Liss and Steve Sherman, p.9-10.

Landfills do not reach 75% gas collection efficiency.
We are attaching Peter Anderson's memo to these comments. He is a landfill expert and thoroughly reviews the issues around LF gas collection efficiency. Please read his memo in conjunction with this section.
In brief the issues are:

- Landfills are not properly enclosed with an impermeable cap until they are closed.
- The majority of a landfill's operating life (62%) occurs before this impermeable cap and LFG collection system are installed.
- EPA has no factual basis upon which it settled on 75%; it represents wishful thinking.
- There are no field measurements of efficiency of landfill gas collection systems.
- The best evidence of lifetime capture rates are closer to 20%.

Given the highly questionable assumptions related to LFG collection efficiency, we believe it is not possible to accept EPA's estimate of 52% of carbon being sequestered in landfills for purposes of the GHG inventory. We recommend a lower percentage.

For these and other reasons, Peter Anderson reaches the conclusion that diverting organics from landfills has 260 times the benefits of LFG to energy collection systems.

The most sustainable climate change strategy is to divert biodegradable organics including food scraps away from landfills to composting or anaerobic digestion. Food waste should first be prevented, then unused food should feed people, then animals. Remaining food scraps should be composted or anaerobically digested and returned to soils.

Returning these nutrients to soils increases soil nutrients, displaces artificial fertilizers, builds soil holding capacity, decreases run-off, increases water holding, fights plant diseases, increases plant growth and food nutrients, while building soil carbon. Building healthy soil from diversion of biodegradable organic materials is a key example of a sustainable system with lots of ancillary benefits for farmers, nursery businesses and the consuming public. Anaerobic digestion also produces methane, which is a renewable energy source that more reliably captures and uses methane than a leaky landfill ever could.

Unfortunately to date, EPA has not captured the multiple environmental benefits of composting in its WARM model. While EPA is attempting to update this model, even the update will not be capable of capturing all of the above benefits. We believe it is possible to capture the sustainable benefits of a system qualitatively first, before you have all of the numeric measurements to complete a quantitative analysis.

Biogenic Emissions

It is critical that biogenic emissions be addressed with a more critical eye. The current treatment of biogenic emissions provides a distinct advantage to incineration. MSW incinerators rely on an unsustainable waste system—a system that emphasizes disposal over waste reduction, reuse and recycling. Because incinerators destroy resources, those resources cannot be reused or recycled. Thus incinerators by destroying resources prevent their handling by more environmentally sound means that preserve resources and energy. The favorable treatment accorded biogenic emissions coupled with the failure to adequately count the benefits of composting serves to disadvantage the most sustainable option for handling organic waste materials.

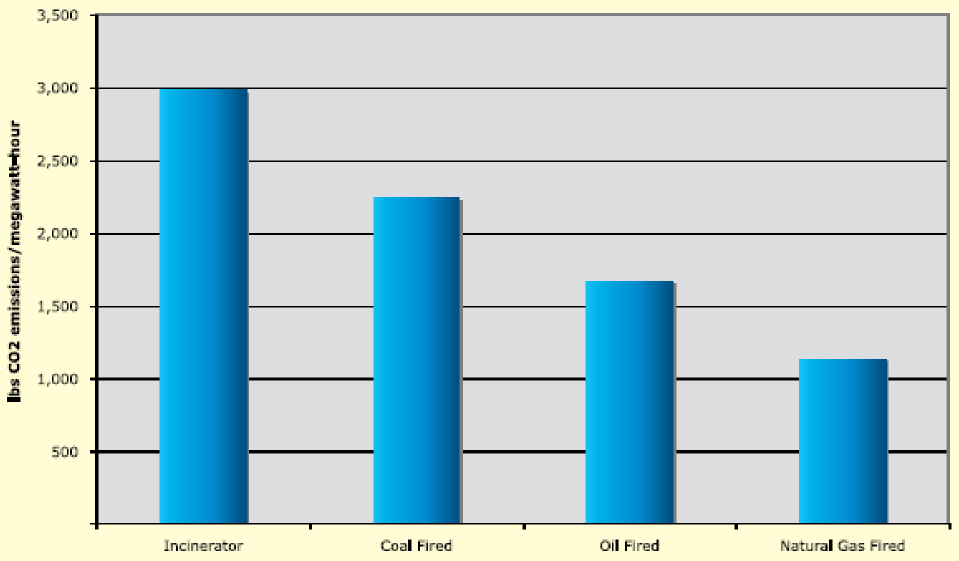
In addition, there is a substantive difference between sustainably harvested biomass and the cutting down of irreplaceable rainforests. As currently handled the treatment of biogenic emissions is a one size fits all. As a result it is ripe for abuse.
Incinerators and other thermal treatments are the most problematic in this regard.

- All such equipment uses fossil fuel to operate, but this is often not quantified.
- What is burned is not just unprocessed biogenic material, but material that has had large energy inputs in the processing to a finished product. The modeling here <u>does not</u> include this embodied energy.

- Raw material resources are destroyed in thermal treatment. To get more paper, cardboard, etc. you have to cut down more trees.
- Green organic materials have a high water content and thermal treatments are using energy largely to remove water.
- There are higher and better uses for all materials to be burned in an incinerator and the processing costs are always less than thermal treatment.

This graph shows the total CO2 emissions of incinerators compared to fossil fuel plants.
Stop Trashing the Climate report

Figure 4: Comparison of Total CO_2 Emissions Between Incinerators and Fossil-Fuel-Based Power Plants (lbs CO_2/megawatt-hour)



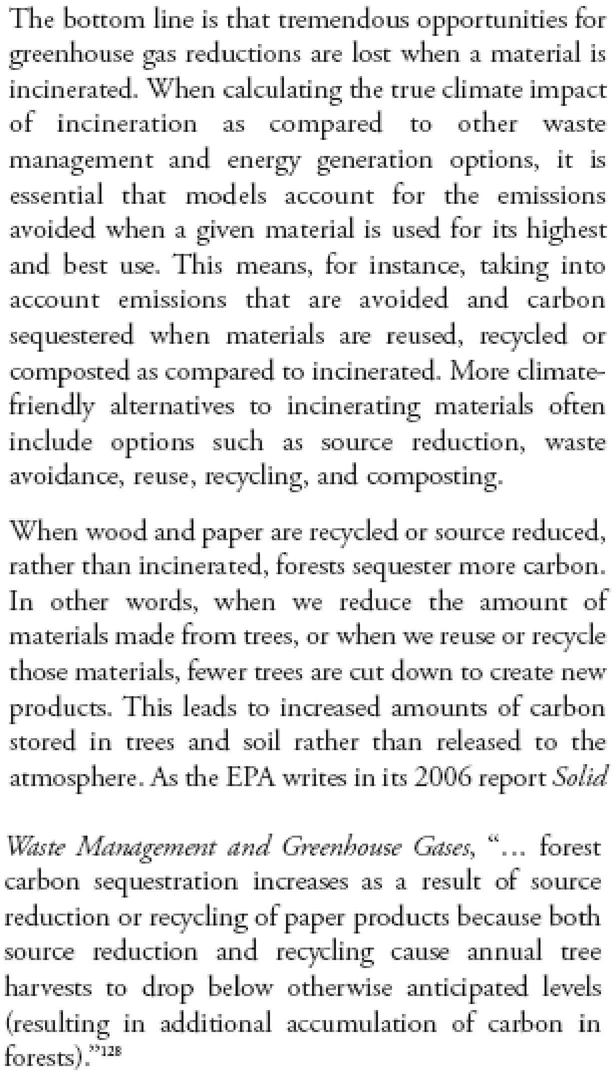
Source: Institute for Local Self-Reliance, June 2008. Based on data reported on the U.S. EPA Clean Energy web page, "How Does Electricity Affect the Environment," http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html, browsed March 13, 2008.

Below are some sections of the report *Stop Trashing the Climate* p. 39-40, which discuss the issue of biogenic emissions. www.stoptrashingtheclimate.org

The rationale for ignoring CO_2 emissions from biomass materials when comparing waste management and energy generation options often derives from the Intergovernmental Panel on Climate Change (IPCC) methodology recommended for accounting for national CO_2 emissions. In 2006, the IPCC wrote:

> "Consistent with the 1996 Guidelines (IPCC, 1997), only CO_2 emissions resulting from oxidation, during incineration and open burning of carbon in waste of fossil origin (e.g., plastics, certain textiles, rubber, liquid solvents, and waste oil) are considered net emissions and should be included in the national CO_2 emissions estimate. The CO_2emissions from combustion of biomass materials (e.g., paper, food, and wood waste) contained in the waste are biogenic emissions and should not be included in national total emission estimates. *However, if incineration of waste is used for energy purposes, both fossil and biogenic CO_2 emissions should be estimated. Only fossil CO_2 should be included in national emissions under Energy Sector while biogenic CO_2 should be reported as an information item also in the Energy Sector.* Moreover, if combustion, or any other factor, is causing long term decline in the total carbon embodied in living biomass (e.g., forests), this net release of carbon should be evident in the calculation of CO_2 emissions described in the Agriculture, Forestry and Other Land Use (AFOLU) Volume of the 2006 Guidelines."[127] *[emphasis added]*

There is no indication that the IPCC ever intended for its national inventory accounting protocols to be used as a rationale to ignore emissions from biomass materials when comparing energy or waste management options outside of a comprehensive greenhouse gas inventory. Rather, the guidelines state "…if incineration of waste is used for energy purposes both fossil and biogenic CO_2 emissions should be estimated."



The bottom line is that tremendous opportunities for greenhouse gas reductions are lost when a material is incinerated. When calculating the true climate impact of incineration as compared to other waste management and energy generation options, it is essential that models account for the emissions avoided when a given material is used for its highest and best use. This means, for instance, taking into account emissions that are avoided and carbon sequestered when materials are reused, recycled or composted as compared to incinerated. More climate-friendly alternatives to incinerating materials often include options such as source reduction, waste avoidance, reuse, recycling, and composting.

When wood and paper are recycled or source reduced, rather than incinerated, forests sequester more carbon. In other words, when we reduce the amount of materials made from trees, or when we reuse or recycle those materials, fewer trees are cut down to create new products. This leads to increased amounts of carbon stored in trees and soil rather than released to the atmosphere. As the EPA writes in its 2006 report *Solid Waste Management and Greenhouse Gases*, "… forest carbon sequestration increases as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests)."[128]

Thank you for your attention. We would appreciate being informed of future developments to improve the greenhouse gas inventory.

Sincerely,

Barbara J Warren

Barbara J. Warren
Executive Director

encl: Factsheet- Waste Impacts Climate Change
Memo prepared by Peter Anderson

Waste Impacts Climate Change

- Wasting directly impacts climate change because it is directly linked to resource extraction, transportation, processing and manufacturing, all of which use energy and generate emissions. Two recent reports examined the greenhouse gas impacts of products and packaging, the first from EPA found 37% of GHGs associated with non-food products and packaging. The second report was a follow-up and included global trade, although food was still not included; it found 44% of GHGs associated with products and packaging. (Both reports available at www.productpolicy.org)

- For every bag of trash a household puts at the curb, 70 bags of trash were created upstream in the production process.

- Zero waste strategies-waste reduction, reuse, recycling, and composting-- are the fastest, cheapest and most effective strategies to protect the climate and the environment. All are associated with greenhouse gas reductions, in addition to many other benefits.

- Using zero waste strategies and significantly decreasing disposal in landfills and incinerators can reduce GHGs the equivalent of closing 1/5 of all US coal-fired power plants. (See www.stoptrashingtheclimate for this excellent report.)

- Waste reduction and material recovery strategies are ESSENTIAL to putting us on a path to stabilize the climate by 2050. Greenhouse gas reductions of 80% are needed and we cannot accomplish this goal without adequately addressing waste.

- Waste incineration and other thermal technologies* do not produce clean, renewable energy. It relies on destroying precious resources, is environmentally polluting and puts out 36% more CO_2 than coal-fired power plants. Recycling is renewable energy saving 4-5 times more energy than an incinerator recovers.

- Biodegradable materials like food and yard waste degrade in landfills and produce methane, a powerful greenhouse gas with 72 times the global warming potential of CO2 over a twenty year period. Adequate control of greenhouse gases is even more essential over the next twenty years, because of the possibility of a runaway situation for warming.

- Landfills even ones with good gas capture systems are able to collect only about 20% of the methane that is generated. (IPCC 4th Assessment, Working Group III, Mitigation of Climate Change, 10.4.2.)

- Composting of biodegradable material results in a valuable product that improves soil-- increasing nutrients, water retention, and healthy plant growth while reducing plant diseases and the need for synthetic fertilizers. Increasing soil carbon is an added climate change benefit.

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*Newer thermal technologies include gasification, pyrolysis, plasma arc and other creative descriptions. All are commercially unproven for mixed waste, but their claims sound wonderful.

Greenhouse gas emissions inventories often inappropriately deal with the issue of Biogenic Emissions.
Biogenic emissions are considered natural emissions from the carbon cycle. However burning waste should not be considered renewable because it relies on the destruction of resources rather than preservation. Often inventories do not count the biogenic emissions (CO2 emissions generated by burning paper, wood, food and yard waste) from incinerators. This could arise from a misunderstanding of IPCC guidance. The IPCC states, " if incineration of waste is used for energy purposes, both fossil and biogenic CO2 emissions should be estimated."

- All incinerators and thermal technologies use fossil fuel to operate, but this is often not quantified.
- What is burned is not just unprocessed biogenic material, but material that has had large energy inputs in the processing to a finished product. Incineration does not recover this embodied energy, but recycling does.
- Green organic materials have a high water content and thermal treatments are using energy largely to remove water.
- There are higher and better uses for all materials to be burned in an incinerator and any alternative processing costs for composting and recycling are always less than thermal treatment.
- Raw material resources are destroyed in thermal treatment. To get more paper, cardboard, etc. you have to cut down more trees. As EPA states, "forest carbon sequestration increases as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests). " *Solid Waste Management and Greenhouse Gases*, 2006 EPA Report.

EPA assumes landfills reach 75% gas collection efficiency. In reality:

- Landfills are not properly enclosed with an impermeable cap until they are closed.
- The majority of a landfill’s operating life (62%) occurs before this impermeable cap and LFG collection system are installed.
- EPA has no factual basis upon which it settled on 75% collection efficiency; it represents wishful thinking.
- There are no field measurements of efficiency of landfill gas collection systems.
- The best evidence of lifetime capture rates are closer to 20%. (IPCC 4th Assessment, Working Group III, Mitigation of Climate Change, 10.4.2.)
- Significant carbon sequestration in landfills is thus highly questionable.

ZERO WASTE STRATEGIES can significantly reduce disposal and greenhouse gas emissions. ZW strategies provide cost savings, while also creating jobs and economic development. ZW strategies are good for New York and good for our climate.

For 2004, New York recycling reduced greenhouse gas emissions by 5,212,571 metric tons of carbon equivalents (MTCE) in a one year period. New York’s recycling saved a total of 230,964,227 Million BTUs of energy. Recycling 811,057 tons of newspapers, phone books, office paper, textbooks, magazines and cardboard in 2004, New York resulting in forest carbon sequestration benefits equal to 54,885,090 tree seedlings grown for 10 years.(Northeast Recycling Council, NY 2004 factsheet.)

Prepared for NY Zero Waste Alliance, managed by Citizens' Environmental Coalition, 33 Central Ave. Albany, NY 12210, 518-462-5527. Contact Barbara Warren also at 845-754-7951 or warrenba@msn.com

Appendix J

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 5
77 WEST JACKSON BOULEVARD
CHICAGO, IL 60604-3590

APR 1 6 2010

REPLY TO THE ATTENTION OF:

L-8J

MEMORANDUM

SUBJECT: Comments on Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008 (March 2010)

FROM: Margaret M. Guerriero, Director
Land and Chemicals Division

TO: Leif Hockstad, OAR Climate Change Division
Brian B. Cook, OAR Climate Change Division

We appreciate the importance of updating the Inventory of U.S. Greenhouse Gas (GHG) Emissions and Sinks (Inventory) and the need to follow IPCC Guidelines and sector categories for consistency with UNFCCC reporting guidelines. We also appreciate your decision to re-allocate the emissions into more commonly used sector categories to improve the usefulness of the Inventory. We recommend that you consider including additional re-allocations, including those presented in Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices, USEPA OSWER, September 2009 (See chart on page 11, www.epa.gov/oswer/docs/ghg_land_and_materials_management.pdf).

Last year, EPA's Office of Solid Waste and Emergency Response completed a peer-reviewed analysis of the U.S. inventory that shows a systems-based view of emissions, "where each system represents and comprises all parts of the economy working to fulfill a particular need." While the current Inventory's sector-based view is helpful for identifying end-of-pipe strategies for reducing emissions within sectors, OSWER's systems-based view is helpful for identifying opportunities to reduce our GHG emissions through prevention-oriented mitigation strategies.

From our perspective, as a regional pollution prevention and sustainable materials management program, the systems view provides more insight to state and local governments, industry, and individuals looking for opportunities to reduce greenhouse gas emissions through policy options and behavior changes. While the draft Inventory acknowledges that the use of scrap material contributed to the decline in emissions from iron and steel production, the sector – based view of the data makes it difficult to identify other areas where material choices may impact emissions. OSWER's systems-based view estimates that 42 percent of the total U.S. GHG emissions are associated with materials management decisions. For a state or local government developing a climate action plan, knowing the relative emissions profiles of various systems (e.g., the provision of goods is responsible for 29 percent of emissions, relative to local passenger transport at 15 percent of emissions) is more helpful than the end-of-life emissions from materials as a result of landfilling, composting, and wastewater treatment provided in the current Inventory. In other words, the current Inventory does not reveal the total GHG emissions associated with goods and services across their life cycle. When viewed by systems, the impacts of consumption on our national GHG emissions are far more impressive, and highlight the importance of reducing both overall consumption and the emissions across the lifecycle of goods and materials.

We encourage you to revise the draft Inventory to include, at a minimum, a reference to this important and insightful EPA, peer-reviewed resource. Ideally, future versions of the Inventory will include both a sector-based and a systems-based view to present a more comprehensive picture of U.S. GHG emissions.

If you have any questions, please contact me, or your staff may contact Julie Gevrenov, of my staff, at (312) 886-6832.

cc: Brigid Lowery, Acting Director, OSWER Center for Program Analysis

United States
Environmental Protection
Agency

Summary of Public Review Comments and Responses:
Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016*

April 2018
U.S. Environmental Protection Agency
Office of Atmospheric Programs
Washington, D.C.

Responses to Comments Received during the Public Review Period on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016*

Preface

EPA thanks all commenters for their interest and feedback on the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Per Federal Register Notice 2018-02546 published on February 7, 2018 the Environmental Protection Agency (EPA) announced document availability and request for comments on the draft “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016” report. The EPA requested recommendations for improving the overall quality of the inventory report to be finalized in April 2018 and submitted to the United Nations Framework Convention on Climate Change (UNFCCC), as well as subsequent inventory reports.

During the 30-day public comment period which ended March 9, 2018, EPA received 37 unique comments in response to the notice. This document provides EPA’s responses to technical comments on methods and data used in developing the annual greenhouse gas inventory. The verbatim text of each comment extracted from the original comment letters is included in this document, arranged by commenter. Full comments can be found in the public docket here: https://www.regulations.gov/docket?D=EPA-HQ-OAR-2017-0729. EPA’s responses to comments are provided immediately following each comment excerpt.

Commenter: Steven C. Beckham

Utah Department of Environmental Quality
Docket ID Number: EPA-HQ-OAR-2017-0729-0019

Comment: The Office of Air and Radiation is to be commended for its Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. Please accept the following analysis as a comment in support of the Draft Inventory.

***Response:* EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.**

Commenter: Trakref

Ted Atwood
Docket ID Number: EPA-HQ-OAR-2017-0729-0037

***Comment*:** The Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016 (hereby referred to as Inventory) does not include usage emissions from CFCs and HCFCs, even though these are two of the most prominent greenhouse gases (GHGs) with significant ozone-depleting potential (ODP) and global warming potential (GWP). Excluding them from the Inventory misrepresents our GHG emissions and means that we are without a clear view of the total GHG inventory. This is where the discrepancy with the refrigerant numbers in the Inventory originates. Thus, the following is argued: 1) the emissions from CFCs and HCFCs should be included in the Inventory and 2) fluorocarbon emissions (CFCs, HCFCs, and HFCs) are undercounted across the board, particularly when factoring in reclaim rates, equipment sales, and leak rates.

***Response*: As indicated by the commenter, EPA does not include emissions from CFCs and HCFCs in national GHG inventories (per UNFCCC reporting guidelines[1]), as these gases are controlled under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Therefore, the United States does not include emissions from CFCs and HCFCs in Table 4-94 of the U.S. GHG Inventory. For informational purposes and completeness, emission estimates of CFCs and HCFCs are summarized in the Inventory in Table A-278 of Annex 6.2 Ozone Depleting Substance Emissions. EPA has included a footnote in the introductory paragraph of section 4.24 referencing the Annex to facilitate finding this information.**

EPA strives to provide the best estimates and are willing to consider any new information—on CFCs, HCFCs, HFCs, or any other chemicals used—to improve our estimates.

***Comment*:** To explain this further, I have included my comment that I submitted on last year's Inventory (i.e., Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015) at the bottom of this message. (While a few variables may have changed, the same underlying message from my comment submitted last year still holds true, which is why I have re-attached it.)

***Response*: Thank you for supplying a copy of your comment on last year's Inventory. You may find EPA's response at: https://www.epa.gov/sites/production/files/2018-02/documents/1990-2015_inventory_public_review_comment_response.pdf.**

***Comment*:** In short, the majority of fluorocarbon refrigerants are not properly destructed at the end of their lives and thus the majority of them end up vented into our atmosphere. More attention needs to be

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[1] https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2

given to the emissions from the consumption of refrigerants in the refrigeration and air-conditioning sector. For example, why does the Inventory spend so much time detailing HCFC-22 Production and the emissions of its byproduct, HFC-23, when the more important issue is the consumption of HCFC-22 in refrigeration and air-conditioning end-uses?

Further, how can we reduce and prevent the venting of millions of pounds of fluorocarbon refrigerants into our atmosphere when the Inventory overlooks the importance of emissions from HCFC-consumption?

***Response*: This inventory assumes all refrigerant consumption is eventually emitted, during either use or servicing, upon equipment disposal, or after accumulation and possible delayed release because of recovery and reclamation in various products and equipment. See Annex 3.9 Substitution of Ozone Depleting Substances of the Inventory report for more information about the assumptions and methodology for emissions estimation. This report provides a robust and accurate accounting for all emissions included, as required by the UNFCCC. The length of the text is as required to explain the methodology and results—it is not a reflection of the relative magnitude of emissions from any given source.**

Further, U.S. regulations establishes several requirements that control the use and emissions of fluorocarbon refrigerants. See 40 CFR Part 82, Subpart F – Recycling and Emissions Reduction or visit https://www.epa.gov/ozone-layer-protection for more information.

Commenter: The Fertilizer Institute (TFI)

Andrew O’Hare
Docket ID Number: EPA-HQ-OAR-2017-0729-0031

Comment: [Draft Inventory Pages 4-24 to 4-25] TFI Supports How Carbon Dioxide Captured During Ammonia Production and Used to Produce Urea Is Treated in the Draft Inventory:

As noted in the Draft Inventory, emissions of carbon dioxide occur during the production of synthetic ammonia through the use of natural gas, petroleum coke, or naphtha as a feedstock. However, the Draft Inventory reporting protocol for ammonia production only accounts for carbon dioxide emissions to the atmosphere. As correctly observed by EPA in the Draft Inventory, “[t]he [carbon dioxide] that is captured during the ammonia production process and used to produce urea does not contribute to the [carbon dioxide] emission estimates for ammonia production presented in the [Draft Inventory].” Rather, carbon dioxide emissions from the manufacture of urea are accounted for either in the Urea Consumption for Non-Agricultural Purposes section or the Agriculture section of the Draft Inventory. TFI supports this accounting, since carbon dioxide is not emitted to the atmosphere from the ammonia source category when the carbon dioxide is captured and used to produce urea.

By Contrast, and As Previously Pointed Out By TFI to EPA, the MGGRP Skews Reported Carbon Dioxide Emissions From Ammonia Production By Requiring Ammonia Producers to Report Captured Carbon Dioxide Used in Urea Production As An “Emission” to the Atmosphere:

The MGGRP for ammonia manufacturing does not distinguish between carbon dioxide emitted during the manufacture of ammonia and carbon dioxide captured during ammonia production and used to produce urea. Rather, all carbon dioxide generated during ammonia production must be reported.6 The result is that this over-reporting of carbon dioxide unfairly prejudices ammonia producers by overestimating their greenhouse “footprint.” In addition, the reporting of carbon dioxide captured during ammonia production and used to manufacture urea is inconsistent with the statements in Subpart G regarding what carbon dioxide emissions ammonia producers must report, namely: (1) process emissions from steam reforming of a hydrocarbon or the gasification of solid and liquid raw material; (2) emissions from each stationary fuel combustion unit; and (3) emissions collected and transferred off-site. Carbon dioxide bound in urea does not fit into any of these categories.

Additionally, the general policy of the MGGRP, as expressed in 40 C.F.R. § 98.1, is to gather greenhouse gas data from "certain facilities that directly emit GHGs . . . ." EPA's stated intent, therefore, is to gather data on "direct emissions," which from a common sense perspective, means releases to the atmosphere. The requirement to report carbon dioxide bound in urea, and not "emitted," is thus inconsistent with EPA's statements.

In part, as a result of EPA's requirement to report carbon dioxide captured and used to produce urea, TFI filed a lawsuit against EPA when it promulgated the MGGRP. Ultimately, TFI and EPA agreed to a comprise to resolve the litigation when the Agency agreed to revise Subpart G to state that reported carbon dioxide emissions "may include [carbon dioxide] that is later consumed on site for urea production, and therefore is not released to the ambient air from the ammonia manufacturing process unit." TFI appreciates the opportunity to provide comments on this Notice and the Draft Inventory, and the need to provide a consistent reporting scheme between the Draft Inventory and MGGRP. We look forward to subsequent dialogue with EPA regarding how to modify the MGGRP, Subpart G so that only carbon dioxide emissions to the atmosphere are reported.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. Comments related to Subpart G have been forwarded to the EPA Greenhouse Gas Reporting Program (GHGRP) as they are out of scope for the Inventory. Any further feedback can be shared with EPA's Greenhouse Gas Reporting Program at https://www.epa.gov/ghgreporting/forms/contact-us-about-ghg-reporting.**

Commenter: National Association of Clean Water Agencies (NACWA)

Cynthia A. Finley
Docket ID Number: EPA-HQ-OAR-2017-0729-0039

Comment: NACWA has previously stated its concern that potentially outdated data were used in the emissions calculations, and this remains a concern with the current inventory. For example, the 1992, 1996, 2000, and 2004 Clean Watershed Needs Surveys (CWNS) are used as the basis for the percent of wastewater flow to aerobic and anaerobic systems, the percent of utilities that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters. The 2004 CWNS is outdated, and forecasts made from it and the previous surveys likely do not accurately reflect recent trends and practices for wastewater utilities.

Response: **EPA continues to search for and review updated sources of activity data for wastewater treatment system type to distinguish between aerobic, anaerobic, and aerobic systems with the potential to generate CH_4. Due to significant changes in format, CWNS data for 2008 and 2012 require additional evaluation to determine a methodology for incorporation into the Inventory. In addition, other data continue to be evaluated to update future years of the Inventory, including anaerobic digester data available at biogasdata.org. EPA will continue to monitor the status of these data as a potential source of digester, sludge, and biogas data from POTWs.**

Comment: The wastewater flow of 100 gal/ person/ day was taken from a 2004 document published by the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental

Managers. Due to droughts and effective water conservation measures, other areas of the U.S. now have wastewater flows significantly less than this value.

Response: **EPA continues to search for and review updated sources of activity data, including improved data on the amount of biogas generated in anaerobic digesters. EPA will continue to monitor the status of data available from biogasdata.org as a potential source of biogas generated from anaerobic digesters, which would obviate the need to use the estimated wastewater flow of 100 gal/person/day.**

Comment: NACWA recommends that EPA consider updating the Metcalf and Eddy (2003) reference to the newest edition of this book.

Response: **EPA will investigate using the most recent Metcalf and Eddy edition to update any remaining Metcalf and Eddy (2003) references.**

Comment: The Association believes that the nitrogen loading rates for N_2O (effluent) are sources incorrectly and that using information from the existing National Pollution Discharge Elimination System database will yield more accurate and justifiable loading rates.

Response: **EPA has considered the suggestion to estimate nitrogen effluent loads based on data reported under EPA's National Pollutant Discharge Elimination System (NPDES) Program. Unfortunately, very few POTWs are required to report their effluent nitrogen concentration or load, and those that do are typically required to meet more stringent limits than the average POTW. At this time, EPA is unable to confirm that these data would be representative of the entire industry. In addition, this would represent a departure from the IPCC accepted methodology, and would require substantiation that it results in a more robust estimation of these nitrous oxide emissions.**

Comment: EPA should also investigate additional references for nitrogen loading rates. As EPA notes in the Inventory, the revisions to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories may incorporate newer scientific information, and the refinement of emissions factors used for wastewater treatment may help to resolve some of the issues with the methodology.

Response: **EPA agrees that the potential refinements to the 2006 IPCC Guidelines will inform how the methodology may need to be revised. EPA continues to evaluate potential new data sources to update and improve the Inventory data as they become available, including improved activity data on wastewater treatment operations as well as nitrogen loading rates. Additional data sources will continue to be researched with the goal of reducing the uncertainty of the estimate of N entering municipal treatment systems, as well as the estimate of N discharged to receiving waters.**

Commenter: Innovation Center for U.S. Dairy

Docket ID Number: EPA-HQ-OAR-2017-0729-0034

Comment: 1. Scope and boundary question

What is the definition of "manure management"? It would be very helpful to provide clear definition and boundary. In this section, land application of manure is not included, land application is included in soil management sector which is aggregated from across species. Dairy farmers manage the whole set of procedures. Manure management means a set of processes, including manure collection, handling, treatment, storage and application. Farmers may go through all of them or in different order.

2. Alignment and consistency

Need greater alignment and consistency (standardization) between agencies, surveys, reports on waste management system (WMS) and regions (for ARMS, NASS, APHIS, and NRCS) For example: Table A-6 the description of WMS will need to communicated well enough to farmers to ensure consistency and accuracy.

WMS calculation supplementary document Table 4, State Distribution Cow Regions, NRCS.
USDA farm production regions:
https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1048013.pdf

3. Report uncertainty, limitations and context (Statement about "EPA GHG inventory report is an abused report")

Report needs more robust section on uncertainty, limitations, could also provide context in how to use this report.

4. Communication and education comments:

Communicating the value of the survey and data gather efforts to farmers is extremely important for the farmers to care, understand the question fully, and answer accurately. Context: NASS workshop learning: ARMS survey takes 3-3.5 hours/farm, it is most difficult to answer.

5. Critical manure related GHG data that is very useful for livestock industry to calculate GHG emissions

More details could be included in Annex. Regarding to livestock manure related GHG emissions, it would be helpful to report manure management (treatment and storage) in chapter 5.2, and also the manure land application in with same level of details in chapter 5.4. Same level of details means report manure land application related GHG emission by state, by animal species, and by crops that receive manure. So that industry could use EPA GHG inventory report to inform their calculation, and make sure a consistent reporting.

6. What's the plan for improvement

a. Report needs more robust section on uncertainty, limitations, could also provide context in how to use this report.

b. Potential data sources (such as the USDA Agricultural Resource Management Survey) for updated WMS distribution estimates have been obtained and discussed with USDA. EPA is working with USDA to review these data sources for potential implementation in future Inventory reports. In addition, EPA may pursue the following improvements in future Inventory years:

I. Define manure management practices with more detailed descriptions, pay attention to farmer's term in different regions.
II. Give some explanation how the EPA inventory allocates to dairy and beef. Apparently, EPA inventory includes ALL animals that originate in a dairy farm are counted as "dairy" even if they end up in the beef supply chain.

III. Implement a methodology to calculate monthly emissions estimates to present data that show seasonal changes in emissions from each WMS.
IV. Revise the anaerobic digestion estimates to estimate CH_4 emissions reductions due to the use of anaerobic digesters (the Inventory currently estimates only emissions from anaerobic digestion systems)
V. Update the B0 data used in the Inventory, which are dated
VI. Compare CH_4 and N_2O emission estimates with estimates from other models and more recent studies and compare the results to the Inventory, such as USDA's Dairy Gas Emissions Model.
VII. Compare manure management emission estimates with on-farm WMS measurement data to identify opportunities for improved estimates.
VIII. Improve collaboration with the Enteric Fermentation source category estimates. For future inventories, it may be beneficial to have the CEFM and Manure Management calculations in the same model, as they rely on much of the same activity data and they depend on each other's outputs to properly calculation emissions.
IX. Changes that have been implemented to the CH_4 and N_2O estimates warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source will be initiated.

c. What's the plan for using/enabling process-based models (mechanistic models) to improve the GHG inventory effort?

I. DACENT is used for crop/soil GHG emission calculation. The manure related GHG emission could also be enhanced by process-based model.
II. For example, NAEMS measurement data was collected, and can NAEMS data or other similar data be used to calibrate models and simulate manure storage, and land application and soil GHG emissions?

Response: **EPA appreciates the commenter's recommendations on improvements to the Manure Management chapter of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, and notes many recommendations are consistent with those already identified by EPA and listed in the draft inventory published for public review. The EPA has added clarity to the improvements listed within the Planned Improvements section of the Manure Management chapter of the current Inventory. EPA is currently reviewing many recommended data sources and improvements for potential implementation in future Inventory reports. Many of these improvements are major updates, including the recommended methodological changes, and may take multiple years to implement in full. Please see *Box 5-2: Biennial Inventory Compilation,* included in the current Inventory report, for more information on the timing of improvements to the Agriculture and LULUCF chapters. In the next Inventory report (i.e., 1990 through 2017), EPA will add clarity to the scope, boundary and methods used for the Manure Management chapter.**

Commenter: Frances Lamberts

Private Citizen
Docket ID Number: EPA-HQ-OAR-2017-0729-0033

Comment: I am glad to see the United States adhering to the commitment made under an earlier Administration, at the Rio Earth Summit treaty, to perform and submit to the United Nations an inventory of our greenhouse gas emissions. Thus, I thank you for publishing the inventory draft.

Taking note that emissions increased in the 2013-14 time span, I see them to have come down from 2015 levels, over the year 2016. That is a positive development which, through further gains in energy efficiency and electricity production from renewable sources, I hope you will promote and strongly support in the years ahead. Our country should accelerate these latter strategies -- energy conservation/ efficiency and renewable sources as much and as quickly as possible, both to counteract the climate troubles we are under as also to save significantly on healthcare costs and avoid many lives prematurely cut short through carbon and related air pollutions.

Response: **EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.**

Commenter: Bridget Chadwick

Private Citizen
Docket ID number: EPA-HQ-OAR-2017-0729-0038

Comment: "…substitution from coal to natural gas and other sources in the electric power sector" (page ES-2)
Please clarify what "other sources" are by describing as either "non-fossil fuel energy" or "nuclear and renewable energy".

Response: **EPA has clarified the text to indicate other non-fossil energy sources on page ES-4 in Section ES-2.**

Comment: Since the Industrial Revolution …global atmospheric concentrations of CO_2 have risen…principally due to the combustion of fossil fuels (page ES-9)" I would add "for energy" to the end of the sentence to differentiate "the combustion of fossil fuels" from the non-energy use of fossil fuels discussed in section 3.2 of the Inventory.

Response: **EPA has clarified the text to indicate for energy on pages ES-9&10.**

Comment: A drop in the carbon intensity of energy consumed "by most sectors of the economy" (page ES-10) Comment: To be more specific, from 2005 to 2016, the carbon intensity of energy consumed by the power sector declined by 21%. Likewise, the carbon intensity of energy consumed by non-transport sectors (residential, commercial, and industrial) that consume significant amounts of electricity declined by 16%, 15% and 14%, respectively.

Response: **EPA has clarified the text to indicate carbon intensity decreased in non-transport sectors on page ES-10.**

Comment: "The fundamental factors influencing emissions levels include: (1) changes in demand for energy; and (2) a general decline in the carbon intensity of fuels combusted for energy" (page ES-10) Comment: "Direct drivers" would be a more accurate description than "fundamental factors.

Response: **EPA has clarified the text on fundamental factors to important drivers on page ES-10.**

Comment: Emissions from fossil fuel combustion (page ES-11)

Comment: Adding bar graphs for total energy consumption (from fossil and non-fossil sources) used by (i) the power sector and end-use sectors; and (ii) all end-use sectors with electricity allocated to each, would provide a more complete picture of energy-related CO_2 emissions. These graphs would tie in with the information provided in Figure ES-13: 2016 US Energy Consumption by Energy Source (Percent).

Response: **Given timing of report these changes were not implemented for this year but can be considered as part of the next Inventory report. However, EPA notes that there are several figures**

that already capture much of this information including for the power sector: Figure ES-8: Electric Power Generation (Billion kWh) and Emissions (MMT CO_2 Eq.) and Figure 3 8: Fuels Used in Electric Power Generation (TBtu) and Total Electric Power Sector CO_2 Emissions. For the residential and commercial sectors: Figure 3 11: Fuels Used in Residential and Commercial Sectors (TBtu), Heating Degree Days, and Total Sector CO_2 Emissions. For the transportation sector: Figure 3 12: Fuels Used in Transportation Sector (TBtu), Onroad VMT, and Total Sector CO_2 Emissions.

Comment: "The type of energy source used to generate electricity is the main factor influencing emissions" (pages ES 12 to 13).

More detail would make this point clearer. The carbon content and amount of fossil fuel energy sources with the following: utility coal, with an average CO_2 emission factor of 95.5 MMT CO_2 per quadrillion Btu and natural gas with a CO_2 emission factor of 53.0 MMT CO_2 produced about 69% and 30% of the power sector CO_2 emissions, respectively. Readers could be referred to Figure ES-6.

Response: **A reference was made to Figure ES-8 for trends in energy sources used to generate electricity and impact on CO_2 emissions on page ES-13.**

Comment: "For example, some electricity is generated through non-fossil fuel options such as nuclear, hydroelectric, wind, solar, or geothermal energy" (page ES-13)

Comment: Electricity generated from non-fossil fuel energy is quite significant (in 2016). I would suggest replacing the words: "some electricity" with some detail on the numbers. For example, in 2016, nuclear and renewable energy sources provided 1,382,566 million kWh of electricity, 35% of total electricity generated, 3,918,231 million kWh (EIA's Feb 2018 Monthly Energy Review (MER), Table 7.2b, Electricity Net Generation: Electric Power Sector). Note that the EIA defines the power sector as: "electricity-only and combined-heat-and power (CHP) plants within the NAICS 22 category whose primary business is to sell electricity, or electricity and heat, to the public" (EIA, 2018).

Response: **A reference was made to Figure ES-8 for trends in energy sources used to generate electricity and impact on CO_2 emissions on page ES-13.**

Comment: Box ES-5: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data (page ES-26)

Comment: Carbon intensity of total energy and energy consumption are the two main direct drivers of energy-related CO_2 emissions. Carbon intensity should be added to the list of variables, under "Energy Use" and the carbon intensity trend line should be presented in Figure ES-6: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product (GDP).

Response: **Given timing of report these changes were not implemented for this year but can be considered as part of the next Inventory report. Furthermore, EPA notes that the text already has some discussion of this driver: "Greenhouse gas emissions in the United States have decreased at an average annual rate of 1.0 percent since 2005. Total energy use and fossil fuel consumption have also decreased at slower rates than emissions since 2005" indicating a decrease in carbon intensity of total energy and fossil fuel consumption.**

Commenter: American Petroleum Institute (API)

Karin Ritter

Docket ID Number: EPA-HQ-OAR-2017-0729-0035

Comment: First, EPA should incorporate a regional approach for key sources that will take into account the lack of uniformity of the industry across the country and provide a more accurate representation of industry activity and current practices. Second, EPA should also review their emission factors annually to account for changing industry practices and technological improvements, such as for well completions and workovers with hydraulic fracturing. Finally, in the interest of transparency, whenever EPA includes significant methodological changes, such as those being considered at this time, the agency should make a rigorous effort to specifically and clearly clarify and describe these methodological changes and their impact on emissions from year to year in 'plain English'.

Response: **EPA received information and data related to the emission estimates through GHGRP reporting, the annual Inventory formal public notice periods, stakeholder feedback on updates under consideration, and new studies. EPA held several workshops and webinars on oil and gas in the Inventory and in June and October 2017, EPA released draft memoranda that discussed changes under consideration, and requested stakeholder feedback on those changes. EPA thoroughly evaluated relevant information available, and made several updates to the Inventory, including: to define an exploration segment separate from production (not a methodological change, but a change in presentation of information); calculate activity and emission factors for well testing and non-hydraulically fractured completions from GHGRP data; using GHGRP data to calculate year-specific emission factors for hydraulically fractured gas well completions and workovers and liquids unloading; recalculate production segment major equipment activity factors using updated GHGRP data; revising activity and CH_4 and CO_2 emissions data for associated gas venting and flaring and miscellaneous production flaring; and calculate new CO_2 emission factors for several sources throughout all segments directly from GHGRP data.**

EPA assessed basin-level data and used a basin level production-based approach for miscellaneous production flaring and associated gas venting and flaring, and has retained the national level approach for liquids unloading. EPA assessed annual emissions data and made changes to use year specific emission factors for liquids unloading and hydraulically fractured gas well completions. For details on these specific changes, see pages 3-72 to 3-73 and 3-87 to 3-91. EPA provided additional documentation on recalculations in this year's inventory (for petroleum systems, see bulleted list on page 3-63, and tables on pages 3-69 to 3-70 and for natural gas systems see bulleted list on pages 3-77 to 3-87, and tables on page 3-85).

Comment: API encouraged EPA to adopt a basin level estimation approach, on either a production or well count basis, to account for regional operating differences and provide a more accurate representation of industry practices. In the Public Review version of the inventory, EPA has incorporated the basin-level approach on a well basis for associated gas venting and flaring and indicates that they are evaluating other changes, such as the production basis recommended by API, for the final inventory. However, by not providing in the draft GHGI a full accounting on how they intend to implement the revisions recommended by API, it is currently impossible to review and confirm these calculations or the potential results that will be published in the final GHGI.

Response: **As noted above, EPA held a stakeholder process on updates under consideration for the 2018 GHG Inventory, and EPA has made changes to use a basin-level, production-based approach for associated gas venting and flaring. Where possible, EPA provided stakeholders with**

preliminary estimates of emissions calculated using various approaches. At the time of the release of the public review draft, EPA had not yet fully assessed the production-based approach for associated gas venting and flaring and did not include detailed information in the public review draft, as it was unavailable at that time. The 2018 final inventory includes detailed discussion and annual emissions and activity data for these revisions, and final memos on updates implemented in the 2018 GHG Inventory are available on EPA's 2018 stakeholder process website, at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2016-ghg.

Comment: API also recommends that 'plain English' descriptions of methodology changes and clarifications of their impact on emission calculations from year-to-year should be placed right upfront in the inventory report where EPA discusses the emission estimates for all the economic sectors. For example EPA should consider including language as follows:
The change(increase) in CO_2 emissions for the Natural Gas Systems and Petroleum Systems are due to implementing the following EPA methodological changes:
1) Added flaring emissions that were previously reported only under Natural Gas production.
2) Added emissions from flaring for petroleum production, natural gas processing, transmission, storage and LNG operations that were not previously reported in the inventory.
3) Revised CO_2 emission estimation methods for associated gas venting and flaring, oil and condensate tanks, gas well hydraulically fractured completions and workovers, pneumatic controllers, pneumatic pumps, and liquids unloading in the Natural Gas and Petroleum production segments to align with the approach applied for CH_4 emission estimates.
4) Added CO_2 emissions for gas processing plant emission sources (emissions from reciprocating compressors, centrifugal compressors, dehydrators, flares, and fugitives were grouped together), blowdowns, and Acid Gas Removal (AGR) units using GHGRP data.
5) Modified transmission GHGRP data.

Response: **EPA has provided additional documentation on recalculations in the GHG Inventory. See new Box ES-3 (pages ES-5 and ES-6) in the 2018 GHG Inventory which lists all GHG Inventory sources with recalculations resulting in an average change over the time series of greater than 10 MMT CO_2 Eq., and page 3-2 which provides information on energy sector sources with recalculations resulting in an average change over the time series of greater than 10 MMT CO_2 Eq. In addition, for more detailed information on recalculations for petroleum systems, see bulleted list on page 3-63, and tables on pages 3-69 to 3-70 and for natural gas systems see bulleted list on pages 3-77 to 3-87, and tables on page 3-85.**

Comment: In general, EPA has improved the transparency of the national inventory by engaging with stakeholders and convening workshops to discuss their planned updates throughout the year. API supports the transparency enabled by Annex 3 Tables 3.5 and 3.6 which provide access to the emission factors, activity data, and resulting CH_4 and CO_2 emissions for every source across the full time series (1990-2016).

Response: **EPA has noted this comment.**

Comment: API has requested that whenever EPA includes significant methodological changes, such as those being considered at this time, the agency should specifically identify and describe these methodological changes from year to year together with the results for each sector. Currently, all emission estimation revisions are addressed under the Recalculations Discussion for each source category and under Section 9, the overall Recalculations and Improvements discussion. For tables summarizing emission estimates for a few sources, EPA has added a line that provides the previous emission estimate for that source (i.e. the emission estimate from the 2017 GHGI), as

EPA has done in Tables 3-43 through 3-48 and Tables 3-64 through 4-69. API recommends including this comparison in tables for all emission sources and compiled emission data that incorporate methodological changes.

Response: **EPA has provided additional documentation on recalculations in the GHG Inventory. See new Box ES-3 (pages ES-5 and ES-6) in the 2018 GHG Inventory which lists all GHG Inventory sources with recalculations resulting in an average change over the time series of greater than 10 MMT CO_2 Eq., and page 3-2 which provides information on energy sector sources with recalculations resulting in an average change over the time series of greater than 10 MMT CO_2 Eq. In addition, for more detailed information on recalculations for petroleum systems, see bulleted list on page 3-63, and tables on pages 3-69 to 3-70 and for natural gas systems see bulleted list on pages 3-77 to 3-87, and tables on page 3-85.**

Comment: In addition, an overall summary table should be provided at the beginning of each source category section to show the impact of changes from the previous inventory report. Abbreviated example tables are provided below for Petroleum Systems and Natural Gas Systems. The suggested tables should provide the previous inventory emissions, the current inventory emissions for the previous year (2015 in this case), and the current inventory emissions for the current year.

Response: **Please see previous comment response.**

Comment: API reiterates that the EPA should carefully analyze and screen GHGRP reported data in order to improve the validity of data used in the national GHGI. Significant improvements have been made in the GHGRP reported gas production volumes. In 2015, the total GHGRP gas production volume was more than 14 times larger than the national gas production volume from the DrillingInfo database. For 2016, the total GHGRP reported gas production volume is 87% of the DrillingInfo gas production volume. However, further work is still needed. For 2016, the total GHGRP oil production volume is just slightly higher (104%) than the total oil production volume derived from DrillingInfo, and there are still individual basins with GHGRP reported gas and crude production volumes that are multiple times higher than volumes from the DrillingInfo database. EPA needs to be diligent in reviewing GHGRP data and working with reporting companies to correct erroneous information.

Response: **The EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.**

Comment: In addition, as EPA is evaluating data available from new studies, it is important to understand the applicability of these studies for a national inventory, especially as they relate to temporal and spatial representativeness concerns. API reiterates the need to vet data from new studies through a multi-stakeholder group prior to using their results for updating the GHGI. API encourages EPA to continue with ongoing stakeholder engagement throughout 2018.

Response: **EPA plans to continue engaging with stakeholders on updates to the GHG inventory.**

Comment: EPA has made significant changes in the estimation methods for associated gas venting and flaring emissions starting with the 2017 GHG Inventory compared to previous years in which they addressed associated gas emissions only from stripper wells. API indicated in comments on the draft 2017 GHGI that this is an area requiring further review since data are now available through the GHGRP. Also, operational practices that result in either venting or flaring are linked to the availability of appropriate infrastructure to capture and use associated gas, rather than vent or flare it, and as a result are highly variable according to regional differences. This is a dynamic situation that varies from year to year and from region to region, and requires further analysis of the information available through the GHGRP.

Response: **As noted above, EPA has implemented a basin-level approach to calculate these emissions, with year-specific data when available.**

Comment: API provided a memo to EPA in October 2017 presenting API's basin-level analysis of the 2015 GHGRP data for associated gas venting and flaring under both a well count and a production volume basis. API recommends that EPA apply a basin level approach and use the volume of oil produced to extrapolate GHGRP data for associated gas venting and flaring emissions for the national GHGI. Emissions from associated gas occur due to CO_2 produced by flaring of gases separated from the production liquids, or venting of CH_4 and CO_2 entrained in the produced hydrocarbon liquids (commonly termed gas-to-oil ratio). Therefore, emissions are directly related to the volume of hydrocarbon liquids produced with associated gas venting and flaring rather than to the number of wells with associated gas venting and flaring.

Response: **As noted above, EPA has implemented a basin-level, production-based approach to calculate these emissions.**

Comment: EPA has adopted the basin level recommendation in the emission estimates provided in the Public Review draft inventory. However, the emissions data are currently extrapolated on a well count basis, which is not directly linked to associated gas emissions. EPA notes that it is evaluating a production-based approach for the final version of the inventory.
For associated gas venting and flaring emissions in the final inventory, EPA should incorporate production-based emission estimates applied at the basin level.

Response: **As noted above, EPA has implemented a basin-level, production-based approach to calculate these emissions.**

Comment: EPA has developed new estimates for CO_2 and CH_4 emissions from miscellaneous production flaring using 2015 and 2016 GHGRP data. API provided a memo to EPA in October 2017, presenting API's analysis of the 2015 GHGRP data for flare stack emissions in petroleum and natural gas production. API recommends that EPA use production volumes to apportion flare emissions between Petroleum and Natural Gas Systems and to extrapolate the flare stack emissions to a national level. API contends that this approach is more robust than using well counts and is consistent with API's recommendation for extrapolating associated gas venting and flaring emissions. This is also an emission source that changes from year to year based on operating practices, and therefore emissions should be estimated annually using the most recent data. In the Draft GHGI, emissions data are currently extrapolated on a well basis at the national level, without a basin-level analysis. EPA notes that it is evaluating a production-based approach and developing emission factors at a basin-level. API recommends developing miscellaneous flare emission estimates using a basin level approach and scaling the GHGRP data to the national level based on production volume.

Table 2 compares API's estimate of national GHG emissions from Flare Stacks to EPA's estimate provided in the Public Review inventory.

Response: **As noted above, EPA has implemented a basin-level, production-based approach, with year-specific data when available to calculate these emissions.**

Comment: EPA's Methodology discussion for Petroleum Systems indicates that emission factors for hydraulically fractured (HF) oil well completions (controlled and uncontrolled) were developed using DrillingInfo data analyzed for the 2015 NSPS OOOOa proposal. EPA has indicated in the Planned Improvements section that they will review GHGRP data for oil well completions and workovers with hydraulic fracturing. API supports this planned improvement. This will provide consistency with the emission factors currently used in the GHGI for gas well completions and workovers with hydraulic fracturing. API also recommends that the emission factors for this source category be updated annually to reflect changes in operational practices. We recognize that these updates will not be incorporated in the final inventory. API looks forward to future dialog with EPA in preparation of the 2019 inventory.

Response: **EPA is considering this update for the 2019 GHG Inventory. For additional information, please see https://www.epa.gov/sites/production/files/2018-04/documents/ghgemissions_additional_revisions_2018.pdf.**

Comment: EPA has developed new emission factors for gas well completions and workovers without hydraulic fracturing using GHGRP data. GHGRP specifies a default emission factor of 3,114 standard cubic feet natural gas per well workover without hydraulic fracturing; while the emission factors used in the GHGI differ each year for 2011 through 2016. API assumes this variability in the emission factor is based on different gas compositions and fractions of completions and workovers that are flared versus vented. API intends to review the emissions data more carefully and provide comments at a later time. We look forward to future dialog with EPA in preparation for the 2019 inventory.

Response: **The variability is based on different gas compositions and different fractions of venting and flaring.**

Comment: API provided a memo to EPA in October 2017 presenting API's analysis of the 2015 GHGRP data for gas well completions and workovers with hydraulic fracturing. In that memo, API pointed out that the most significant driver for the difference between EPA's emission estimates and API's estimates is that EPA's emission factors continue to be based on an average of GHGRP data from 2011-2013. API demonstrated that applying the average from these three years clearly overestimates emissions for 2014 and 2015. In addition, EPA includes all GHGRP reported data from 2011-2013, which is comprised of completions in both gas and oil formations, prior to the requirement for separate reporting of emissions from oil completions with hydraulic fracturing.

API recommends developing separate emission factors specific to completions and workovers with hydraulic fracturing for oil formations and gas formations. API also recommends that the emission factors for this source category should be updated annually. Such an approach will reflect current, dynamic trends in completion and workover practices with hydraulic fracturing, mainly due to regulations that now require the use of reduced emission completions (RECs). EPA indicates that they are considering year-specific GHGRP-based emission factors for this source.

For completions and workovers with hydraulic fracturing, API recommends developing separate emission estimates for oil well versus gas well completions. These emission factors should be updated annually with current GHGRP data to reflect changing industry practices.

***Response:* As noted above, EPA calculated HF gas completion emissions using an annual emission factor approach. EPA plans to assess HF oil completions data for updates to the 2019 GHG inventory. For additional information, please see https://www.epa.gov/sites/production/files/2018-04/documents/ghgemissions_year_specific_2018.pdf and https://www.epa.gov/sites/production/files/2018-04/documents/ghgemissions_additional_revisions_2018.pdf**

Comment: Liquids unloading operations are not conducted uniformly across the natural gas production regions of the U.S. and have changed dramatically over the years GHG reporting has been required for natural gas production operations. API provided a memo to EPA in October 2017 presenting API's analysis of the 2015 GHGRP data for liquids unloading and recommended extrapolating emissions from liquids unloading at the basin level for those basins with the most significant contribution to emissions. API recommends that these emission estimates be performed on a well count basis since emissions from liquids unloading are related to the number of liquid unloading events and are not directly or inversely related to gas production rate. In addition, due to changes in liquids unloading operations over time, API recommends that the emissions be evaluated each year. EPA's current emission factors are based on an average of the 2011-2015 GHGRP data which biases the emission estimates high for 2014 and 2015.
EPA indicates that they are considering region-specific emission factors and activity factors for this source.

API reiterates our recommendations that emissions associated with liquids unloading be evaluated on a well-count basis at a basin level and updated each year in order to reflect geographic variability and changes in venting practices associated with liquids unloading rather than using averaged historical data.

Table 3 compares API's emissions (using a basin-specific approach applied annually) to EPA's emissions which are based on an average of the 2011-2015 GHGRP data.

***Response:* As noted above, EPA has calculated these emissions using an annual emission factor approach. EPA assessed these emissions at the basin level and found them to be similar to emissions calculated at the national level (e.g. within about 5%) and has retained the national level approach.**

Comment: Equipment Counts: EPA notes that activity factors were recalculated using the latest GHGRP reporting year (RY) "2015 data" (ENERGY page 3-87, line 31). Since RY 2016 GHGRP data are now available, API requests that the latest GHGRP data be used to establish equipment counts. Or, if this is a misprint, API requests correcting the reporting year cited in the final inventory report.
API requests clarification of what year is used for developing equipment counts.

***Response:* EPA clarified that the method uses the resubmitted GHGRP 2015 equipment count data for these sources. Those equipment counts are applied to years 2011-forward, while earlier years use GRI equipment counts and interpolation. For more information on this approach and other options considered, please see pages 2-3 of the memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Additional Revisions Considered for 2018 and Future GHGIs," available at https://www.epa.gov/sites/production/files/2018-04/documents/ghgemissions_additional_revisions_2018.pdf.**

Comment: EPA developed emission factors for abandoned wells using data from Kang et al. (2016) and

Townsend-Small et al. (2016). API notes that the studies conducted so far have limited geographical coverage, with the University of Cincinnati study having the broadest coverage with 138 abandoned wells in four basins, where a total of 9 wells have been identified as leaking CH_4. To date no data are available from the state of Texas or many other major producing areas, which makes it unrealistic and unrepresentative to extrapolate the results of the current studies to a nationwide estimate of the contribution of CH_4 emissions from Abandoned Wells in the GHGI. API contends that this is an area that requires further study as it is well recognized that many attributes can influence leakage from abandoned wells, including depth, plugging status, well type (oil or gas), geographic location, and abandonment method. Therefore, determining a robust estimate for a national count of abandoned wells throughout the time-series will be challenging. API cautions EPA that current studies have focused on very old wells and the data obtained are limited in scope, limited geographically, and should not be extrapolated broadly.

Response: **EPA assessed data and methodologies for abandoned well emissions and engaged with stakeholders on this emission source throughout the development of the 2018 GHG Inventory. Taking stakeholder feedback into account (including feedback on approaches for using regional data, approaches for calculating the population of older abandoned wells, and approaches for calculating the fraction of wells that are plugged), EPA has incorporated an estimate for abandoned wells into the 2018 GHG Inventory and has calculated an uncertainty range associated with that estimate of -83% to +215%. EPA will continue to look for new data on abandoned wells and make revisions to the sources in future GHG inventories as appropriate. See pages 3-96 to 3-100.**

Comment: EPA continues to evaluate emission sources that currently use voluntary reduction data to identify where an emission source's calculation methodology could be updated to calculate net emissions. EPA notes two areas of corrections in the Public Review draft inventory. In the Production segment, a spreadsheet error resulted in a miscalculation of the scaling factor for the "other reductions". In the Transmission and Storage segment, Gas STAR reductions were not removed for data where the emissions are recalculated using a net emission approach.
API agrees that many emission sources in the GHGI are now calculated using net emissions approaches, with technology-specific activity data and emission factors, and annual data from the GHGRP. For these emission sources it may not be necessary to adjust for Natural Gas Star reductions, which may result in double-counting of reductions. Removing the Natural Gas Star reductions from these sources would improve transparency of the results and methods by relying on direct net emission calculations. However, where applicable, EPA should continue to apply the Natural Gas Star reductions for those specific sources for which only potential emission data is available.

Response: **EPA has removed Gas STAR reductions that were incorrectly applied to net emissions sources.**

Comment: Page 3-67, lines 7-9. API suggests the following insert:
Petroleum systems includes emission estimates for activities occurring in petroleum systems from the oil wellhead through crude oil refining, including activities for crude oil exploration, production field operations, crude oil transportation activities, and refining operations.

Response: **EPA has incorporated the suggested edit, on page 3-65.**

Commenter: Waste Management et al.

Kerry Kelly

Docket ID Number: EPA-HQ-OAR-2017-0729-0032

Comment: We are pleased that in response to the analysis, the 2018 Inventory employs a lower scale-up factor of nine percent as compared to the use of 12.5 percent in the previous year's inventory. Nonetheless, the analysis conducted for the Agency warrants an even lower scale-up factor of five percent as we recommended.

As part of the expert review of the draft 2018 Inventory, the landfill sector recommended that EPA recalculate the scale-up factor using Option (a) and an adjusted WIP amount that was at least 60 percent lower than the amount assumed in the Agency's previous calculation. This reflected the findings that over 60% of assumed waste-in-place was in error due to problems with the EPA database. EPA's assessment of non-reporting MSW landfills shows that the GHGRP captures most emissions from the MSW landfills and a scale-up factor of no greater than five percent would be far more appropriate for use in the Inventory.

Response: **EPA appreciates the commenter's feedback supporting planned improvements for estimating emissions from landfill in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. EPA also appreciates the effort undertaken by the landfill industry to review the list of landfills that do not report to the GHGRP and the attempt to remove reporting landfills and duplicates, as well as fill in missing waste-in-place and open/closure year data where available. Based on further review within EPA and industry input, EPA has revised the scale-up factor used in the emissions estimations for 2004-2016 in the time series from 12.5% to 9%. Please refer to the Recalculations Discussion in Section 7.1 of the Inventory text as well as the supporting memo "Methodological refinements as applied in the 1990-2016 estimates of U.S. greenhouse gas emissions from MSW landfills to account for emissions from facilities not reporting to the Greenhouse Gas Reporting Program" from Kate Bronstein and Meaghan McGrath of RTI International to Rachel Schmeltz of EPA/CCD, April 4, 2018 for more detail on the steps taken to refine the scale-up factor and additional steps that may be taken in the future to further refine the scale-up factor as appropriate.**[2]

Comment: The landfill sector is pleased that EPA is considering revisions to the value of the oxidation factor used for the earlier time series. During the Agency's expert review process on the draft 2018 inventory in late 2017, EPA posed several questions about the inclusion of two oxidation factors: one for waste disposed at facilities with landfill gas collection and control systems (GCCS), and the other for landfills without GCCS. EPA acknowledged that the Agency has not developed a way of assigning a percentage of waste disposed in landfills with gas collection or without for those years. The landfill sector provided comments in opposition to establishing methane oxidation factors based predominantly on the presence or absence of gas collection systems. Nonetheless, EPA notes in Chapter 7 that it is investigating trends in landfill gas collection and control and other factors to evaluate applying differing oxidation factors, and we find this troubling as the Agency lacks the data and a peer-reviewed method for doing so.

Response: **EPA appreciates commenter's feedback on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016 and that the existence of a GCCS is not the sole factor in estimating the amount of methane oxidation. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently**

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[2] https://www.epa.gov/sites/production/files/2018-04/documents/rti_2018_scaleupfactor_memo_final_4-4-18.pdf

used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.

Comment: Regarding the oxidation questions posed during the expert review:
1) Are there available data sources to address trends in installation of landfill gas collection systems?

The landfill sector is not aware of sources that would provide information on the extent of landfill gas collection within the industry or the trends in gas system installation outside of the reporting landfills in the GHGRP. The EPA LMOP dataset only indicates whether a landfill has a gas collection system, but does not note the date of installation or expansion.

Response: **EPA appreciates commenter's feedback and takes note that the commenter is not aware of any data sources to address trends in installation of landfill gas collection system. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: 2) Is it appropriate to assign oxidation factors for landfills with and without landfill gas collection systems?

The landfill sector does not think that it is appropriate to assign oxidation factors to a landfill based solely on whether it operates a GCCS. As explained above, other site-specific landfill attributes, such as WIP, type and extent of cover and modeled methane generation are also important factors in assessing potential methane oxidation. Developing an accurate estimate of methane oxidation is significantly more complicated than relying on whether the landfill has a gas collection system.

Response: **EPA appreciates commenter's feedback on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016 and that the existence of a GCCS is not the sole factor in estimating the amount of methane oxidation. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: 3) What is an appropriate oxidation factor if only one factor is used for all waste disposed between 1990 and 2004?

The existing Subpart HH treatment of methane oxidation requires knowledge of landfill attributes to calculate methane flux and assess the corresponding methane oxidation value based on the bin approach. The bin approach is a conservative estimate based on 800 field estimates of oxidation for a range of methane flux results, as provided in the SWICS addendum and RTI memo. It is our view that EPA should use the flux-based oxidation factor, as it could be applied more broadly than the current application in Subpart HH and is the most defensible approach.

Response: **EPA appreciates commenter's feedback on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: 4) Should a factor be applied to address methane leakage from cracks and fissures in landfill cover when assigning oxidation rates?

We do not understand how the Agency could know or even estimate the extent of cracks and fissures at landfills on a site-specific basis or more broadly on a nationwide, inventory basis. Furthermore, there is no proven or accepted method to determine leakage from cracks and fissures. The reason is that the flux through the cover (and the fraction oxidized) is dependent upon the interactions among many factors, including soil and physical properties of cover such as gas porosity; organic content and moisture; microbiological factors such as temperature and substrate availability; and the presence or absence of a gas collection system. In a 2011 paper in Environmental Science & Technology, researchers looked at the surface air methane 13C value at 20 landfills and found that the oxidation percentage was 36%, as compared to an oxidation rate of 37% measured in surface chambers. Based on this result, methane emitted via cracks and fissures did not appear to be a significant factor, and the presence of cracks and fissures did not necessarily result in higher emissions or lower oxidation.

The landfill sector does not support the development of additional leakage factors for landfills because leakage is already reflected in the calculated flux rates. The higher the flux rate the lower the oxidation rate. We think it is neither valid, nor reasonable to develop leakage factors beyond the GHGRP flux rate calculations for determining an appropriate methane oxidation rate, without extensive scientific support.

Response: **EPA notes commenter's feedback on developing an additional leakage factor when assigning oxidation rates as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: **Degradable Organic Carbon (DOC)**

Chapter 7 explains that EPA uses one DOC value of 0.20 to calculate emissions for the years 1990 through 2004 and uses emissions reported through the GHGRP for years 2005 through 2016. The GHGRP allows landfills to use 0.20 for bulk MSW or allows a landfill to further delineate waste streams by accounting for shipments of C&D waste, which uses a DOC of 0.08, and inert wastes, which may use a DOC of 0.0. If a landfill delineates in this way, it must use a DOC of 0.31 for its MSW waste volumes, which applies an artificially high DOC to MSW, and inappropriately overestimates emissions. We are pleased to read that EPA plans to revisit the DOC value of 0.20 used in the early years of the inventory. However, the Agency should also reevaluate the DOC values incorporated in the GHGRP, as they too need to be updated.

In 2016, the Environmental Research and Education Foundation (EREF) undertook a state-based study of DOC values for both MSW Only Landfills and Non-MSW Material going to MSW Landfills. The DOC guideline recommended by EPA for MSW Only Landfills is 0.31 and the recommended guideline for Non-MSW material going to MSW landfills is 0.20. As described below, these guidelines over-estimate the amount of organic waste deposited in landfills, which results in inaccurate estimates of landfill gas generation and methane emissions. We note that neither of the recommended DOC guidelines have been reviewed by EPA in many years, and we support EPA's view that it is time to update the DOC values.

Response: **As stated in the Planned Improvement section of Section 7.1 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, the Inventory currently uses one value of 0.20 for the DOC for years 1990 to 2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide). EPA also notes the longer term recommendation from the commenter regarding DOC values used in the GHGRP, in the context of the new information on composition of waste disposed in MSW landfills, these newer values could then be reflected in the 2005 and later years of the Inventory.**

Comment: Based on this review of the DOC values for MSW landfills, the landfill sector concludes that the long-standing DOC values developed in the past are inaccurate and are likely to over-estimate both landfill gas generation and methane emissions. The data provided by EREF confirms that two trends are driving the changes at MSW Landfills. First, many MSW Landfills are handling less organic matter now, and this trend is anticipated to continue due to state and local organics diversion goals, and second, the increase of Subtitle D non-MSW waste disposed has altered the DOC for all waste deposited in MSW Landfills. EPA validates these trends in the Inventory's Chapter 6 discussion of carbon sequestration of harvested wood products, yard waste and food waste, which shows a significant reduction in sequestered carbon since 1990 due to reduced volumes of organic wastes disposed in landfills.

Based on EREF's research, we urge EPA to update the DOC values to reflect significant changes in the amounts and types of organic materials being landfilled over the last several years. The values now in use are inaccurate and should not be used going forward. We request that EPA review and update the DOC values in not only the next version of the GHG Inventory, but also update the DOC values used in calculating GHG emissions under Subpart HH of the GHGRP.

Response: **As stated in the Planned Improvement section of Section 7.1 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, the Inventory currently uses one value of 0.20 for the DOC for years 1990 to 2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide). EPA also notes the longer term recommendation from the commenter regarding DOC values used in the GHGRP, in the context of the new information on composition of waste disposed in MSW landfills, these newer values could then be reflected in the 2005 and later years of the Inventory.**

Comment: Further, as EPA clearly recognizes that the composition of the waste at MSW Landfills has changed and continues to change, we suggest the Agency add an additional factor, "(5) the composition of the waste" to the sentence on line 1, page 4 of the waste chapter that begins: "Methane generation and emissions from landfills are a function of several factors."

Response: **EPA appreciates and agrees with commenter's suggestion and has revised the section referenced such that item (1) in the list of factors now reads "the total amount and composition of waste-in-place…"**

Comment: The landfill sector strongly supports EPA's plans to review these k values against new data and other landfill gas models, as well as assess the uncertainty factor applied to these k values in the Waste Model. We have been concerned that these k-values are outdated and rife with uncertainty. The landfill sector has previously highlighted the significant issues with the k values used in the Draft AP-42 Section 2.4: Municipal Solid Waste Landfills. In fact, EPA has never finalized AP-42 for MSW landfills, despite the k-value issues identified by EPA in both AP-42 and the Background Information Document. With uncertainties in CH_4 emissions ranging from -30% to 400% under EPA's assessment of the LandGEM model, it is difficult to take these data seriously. For this reason, we support EPA's plan to review and resolve the significant problems in the k value data set.

Response: **As stated in the Planned Improvement section of Section 7.1 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, in a future Inventory cycle, EPA will review the k values for the three climate types (dry, moderate, and wet) against new data and other landfill gas models, and how they are applied to the percentage of the population assigned to these climate types. EPA will also assess the uncertainty factor applied to these k values in the Waste Model. A 30 percent uncertainty factor is applied to each k value in the Monte Carlo analysis, which is consistent with that recommended by the IPCC (2006).**

Other Comments

EPA received 28 additional anonymous public comments[3] as part of the public review of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016*. These comments can be found on the public docket. Example topics of comments included: production and impacts of rare earth metals, evaluation of various U.S. Federal Government regulations, extreme weather events and climate variation, wind and hydroelectric power, U.S. manufacturing and infrastructure needs, particulate matter air quality, and U.S. energy policy needs.

***Response*:** **These comments are noted but are out of scope of this review**.

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[3] EPA docket IDs for these other comments include: EPA-HQ-OAR-2017-0729-0002; EPA-HQ-OAR-2017-0729-0003; EPA-HQ-OAR-2017-0729-0004; EPA-HQ-OAR-2017-0729-0005; EPA-HQ-OAR-2017-0729-0006; EPA-HQ-OAR-2017-0729-0007; EPA-HQ-OAR-2017-0729-0008; EPA-HQ-OAR-2017-0729-0009; EPA-HQ-OAR-2017-0729-0010; EPA-HQ-OAR-2017-0729-0011; EPA-HQ-OAR-2017-0729-0012; EPA-HQ-OAR-2017-0729-0013; EPA-HQ-OAR-2017-0729-0014; EPA-HQ-OAR-2017-0729-0015; EPA-HQ-OAR-2017-0729-0016; EPA-HQ-OAR-2017-0729-0017; EPA-HQ-OAR-2017-0729-0018; EPA-HQ-OAR-2017-0729-0020; EPA-HQ-OAR-2017-0729-0021; EPA-HQ-OAR-2017-0729-0022; EPA-HQ-OAR-2017-0729-0023; EPA-HQ-OAR-2017-0729-0024; EPA-HQ-OAR-2017-0729-0025; EPA-HQ-OAR-2017-0729-0026, EPA-HQ-OAR-2017-0729-0027; EPA-HQ-OAR-2017-0729-0028; EPA-HQ-OAR-2017-0729-0029; EPA-HQ-OAR-2017-0729-0030.

EPA
United States
Environmental Protection
Agency

Summary of Expert Review Comments and Responses:
Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016*

April 2018
U.S. Environmental Protection Agency
Office of Atmospheric Programs
Washington, D.C.

Responses to Comments Received during the Expert Review Period on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016*

Preface

EPA thanks all commenters for their interest and feedback on the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks. In an effort to continue to improve the estimates in the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks, EPA distributed draft chapters of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016* for a preliminary Expert Review of estimates and methodological updates prior to release for Public Review. The Expert Review ranged from 15 to 30 days by sector, and included charge questions to focus review on methodological refinements and other areas identified by EPA as needing a more in-depth review by experts. The goal of the expert review is to provide an objective review of the Inventory in order to ensure that the final Inventory estimates and document reflect sound technical information and analysis.

EPA received 61 unique comments as part of the expert review process. The verbatim text of each comment extracted from the original comment letters is included in this document, arranged by sectoral chapters. No comments were received on the Draft Agriculture Chapter. EPA's responses to comments are provided immediately following each comment excerpt. The list of reviewers, dates of review and all charge questions distributed to reviewers are included in the Annex to this document.

Chapter 3. Energy

3.1 CH_4 and N_2O from Mobile Combustion - Methodological Updates in Response to Changes to FHWA's Gasoline Consumption Estimation Models

Comment: Decision to Update Data is Clear
Generally, the proposal to update the historical (1990-2015) motor gasoline time series data by incorporating estimates of historic lawn and garden and recreational vehicle fuel use from the EPA's NONROAD model is relatively clear and transparent. Given that the last "major" update of the NONROAD model occurred in 2008, it is likely that the version that was embedded into MOVES for the release of MOVES2014a is very outdated. Therefore, EPA should devote an effort to ensuring that: (a) its estimates using the NONROAD version of the model that is embedded in MOVES are based on updated estimates of equipment populations, activity, fuel efficiency and emission factors, and (b) the latter are consistent with the data, methodology and assumptions used by FHWA for its estimates of non-highway gasoline usage.

Response: **Although the NONROAD model was incorporated into the MOVES platform in 2014, much of NONROAD's underlying equipment population and activity data are 15-20 years old. EPA is currently developing updated non-road population and activity databases (as well as emission rates), which will be available in future versions of MOVES.**

3.1 CH_4 and N_2O from Mobile Combustion - Updated Methodology for Estimating CH_4 and N_2O Emissions from Alternative Fuel Vehicles

Comment: Reporting Use of RNG in On-Road Vehicles
Based on our review by expert colleagues at Natural Gas Vehicles for America ("NGVAmerica"), which includes many AGA member companies, AGA requests that EPA ensure that the Inventory accounts for the use of Renewable Natural Gas ("RNG") in on-road natural gas vehicles. It is not clear to us whether this has been done, and if so, where this data will be reflected in the Inventory. As the recent September 2017 EPA-AGA Renewable Natural Gas Workshop[1] illustrated, there is increasing interest in using purified biogas from landfills, waste water treatment plants and anaerobic digesters as a source of renewable vehicle fuel. RNG used in natural gas vehicles now accounts for roughly 20 percent of the fuel consumed in on-road NGVs, and the percentage is increasing every year. It is important for the Inventory to report the growing use of RNG in on-road vehicles and the related reduction in GHG emissions from vehicles.

[1] See EPA Methane Challenge outreach and events web page at http://www.ttemidev.com/rng/workshop/

Response:
EPA will continue to research options for breaking out vehicles fueled with renewable natural gas.

Comment: Updated Data Available for GREET
This document proposed to rely on GREET 2016 for generating updated CH_4 and N_2O emission factor estimates for alternative fuel vehicles. Argonne National Laboratory recently released GREET 2017 which is an updated version of GREET 2016. EPA should rely on the most current version of GREET available.

Response: **Efforts to develop updated CH_4 and N_2O emission factors for AFVs precede the October 9, 2017 release of GREET 2017. EPA does, however, continue to endeavor to utilize the most up-to-date data sources and calculation methodologies to produce this Inventory.**

Comment: Numbering of Tables Inconsistent
The numbering of the tables in the text of the subsection labeled "CH_4 and N_2O Emissions by Vehicle and Fuel Type" is not consistent with the table numbers shown in the titles of the tables displayed.

Response: **EPA thanks commenter for feedback. Additional text has been added to the "CH_4 and N_2O Emissions by Vehicle and Fuel Type" portion of the memo to more clearly indicate that the "current" emission factors given in Table 6 are those which are described on Page 4 of the memo. Additionally, the captions for Tables 7 and 8 have been modified to reflect that these tables display "updated" emission factors, per the text description on Page 5.**

Comment: Additional Text Needed for Clarity
In general, this document would benefit by additional text which more clearly explains the data and assumptions which underlie each of the steps used to estimate CH_4 and N_2O emissions from alternative fuel vehicles.

Response: **EPA thanks commenter for feedback and will consider this for the current and future reports.**

Comment: Question about Reviewing EIA and GREET Estimates
Pg. 1, 2nd para: EPA states the following - "For VMT, energy use from EIA is divided by fuel economy estimates from GREET to determine miles driven by fuel and vehicle class. Emission factors are determined directly from GREET."

In performing the above calculation of VMT, EPA is implicitly assuming that EIA energy use values and GREET fuel economy estimates are derived from identical populations of alternative vehicles disaggregated by fuel and vehicle class. Has EPA checked the data and methodologies that underlie the EIA and GREET estimates to verify that this assumption is correct? It may be appropriate to run some sensitivity cases to determine the impact of this assumption on the final results.

Response: **EPA thanks commenter for the suggestion to conduct additional analyses to determine the extent to which energy use data from EIA and fuel economy values from GREET rely on similar populations of AFVs. Such an analysis was not within the scope of this update.**

Comment: Suggestion to Include Referenced Regression
Pg. 1, 2nd para, last sentence: It would be helpful to include a copy of the referenced regression analysis and related regression equation statistics (e.g., R2 values) in an Appendix to this document.

Response: **Regressions were performed, but details were not kept. The best fit was used in all cases.**

Comment: Question about Data Comparison of Biodiesel Consumption
Did EPA compare the results of its regression analysis-based estimate of biodiesel consumption in 2000 with actual data?

Response: **This comparison was not performed and was not within the scope of this update. EPA will investigate data sources appropriate for conducting such a comparison, for possible inclusion in future reports.**

Comment: Data Requested for EVs and PHEVs
Pg. 2, 1st para: EPA states the following assumption - "Fuel use per vehicle for EVs and PHEVs were assumed the same as those for the public fleet vehicles surveyed and provided by EIA. This may overestimate electricity usage as it is likely that fleet vehicles accumulate more annual mileage than personal vehicles."

EPA should provide a range of values of the likely overestimate, especially for long range vehicles such as Tesla S.

Response: **While a comparison of accumulated mileage of fleet vs. personal EV and PHEV vehicles would likely complement this memo, such an analysis is not within the scope of this work.**

Comment: Further Elaboration on Table 2 Suggested
Pg. 2, Table 2: Table 2 is presented with virtually no explanation as to how the data which it contains are being used in the analysis. How do EDTA data on annual sales of light-duty EV and PHEVs relate to the EIA data tables on vehicle "counts?" It seems that sales data are being used interchangeably with vehicle stock (i.e., vehicles in operation) data? Is this correct? If yes, then some additional explanatory text should be incorporated into this document, for it is currently very vague and unclear with respect to methodology.

Response: **Cumulative PHEV and EV sales data are used to define vehicle counts. From 2011 onward, EPA assumes no vehicle scrappage. EIA data is used only to determine fuel/electricity use per vehicle (it assumed that vehicle counts from EIA undercount EVs and PHEVs because only fleet vehicles are included). EPA recognizes that future Inventories will need to account for vehicle scrappage.**

Comment: Question about Years in Table 1
Pg. 5, Table 1: What calendar year is being represented by the values shown in this table? i.e., what does "current" mean in the context of calendar year representation? Such information would be useful in the context of understanding the differences between the table on p. 5 and the tables shown on subsequent pages.

Response: Clarification on Timing Language
"Current" in the context of Table 6 refers to emission factors that have been used to develop past Inventories, through the 1990-2015 Inventory report. Should EPA adopt the emission factor updates described in the memo, the "current" emission factors in Table 6 would then be characterized as "previous."

3.1 CH_4 and N_2O from Mobile Combustion - Updated Non-Highway CH_4 and N_2O Emission Factors

Comment: Proposal Written Clearly
Generally, the proposal to update the non-highway CH_4 and N_2O emission factors is written clearly, comprehensively and transparently.

Response: **EPA appreciates the feedback.**

Comment: Question about Non-Highway Emission Factors

What, if any, effort has EPA made to validate that the "new" non-highway CH_4 and N_2O emission factors for each of the non-road equipment types mentioned in this update are indeed representative of actual, real world operation? It would be useful to reference any such studies, research, etc., that support the "new" estimates of emission factors that are shown in this paper.

Response: **Due to a scarcity of in-use data of CH_4 and N_2O emissions from non-highway sources, EPA has not attempted to validate the updated CH_4 and N_2O emission factors described in the memo. Should in-use data become available in the future, EPA may attempt to validate the emission rates described in this memo.**

Comment: Suggestion to Add a Footnote to Tables
Given the significant changes in CH_4 and N_2O emissions that are shown for some categories in Tables 6,7,13 and 22 that are attributed to the change from "current" to "new" emission factors, it would be useful to include a footnote to each of these tables that emphasizes the fact (if true) that no other changes (i.e., to population and/or activity) were made that impact the comparisons.

Response: **EPA agrees that the memo would benefit from table footnotes affirming that results shown in the tables reflect only changes to emission factors and not from any changes to vehicle population and activity inputs.**

3.1 CH_4 and N_2O from Mobile Combustion - Updated On-Highway CH_4 and N_2O Emission Factors

Comment: Proposal Written Clearly
Generally, the proposal to update the on-highway CH_4 and N_2O emission factors is written clearly and transparently. The methodology, data and assumptions used in the update are presented in an organized, concise manner and they are well-documented by statistical analyses included in the appendices.

Response: **EPA appreciates the feedback.**

Comment: Possible Typo or Transcription Error
Pgs. 2-3, Tables 2 and 3: the ~+7-fold increase in HDGV CH_4 emissions due to the use of "new" versus "current" emission factors that is shown in Table 3 is extremely surprising (and very suspect) given the general reduction in methane emission factors (on the order of 0-76%) for this vehicle category that is shown in Table 2. Is this a typo or transcription error? Are there other factors that accompanied the use of updated emission factors (e.g., changes in activity, vehicle population, etc.) that have not been explained?

Response: **Thank you for identifying a critical typo in Table 3. The "current" CH_4 emissions for HDGVs should be 1,551 metric tons, not 23,383 metric tons. The results presented in Table 3 reflect changes to emission factors only (i.e., vehicle population and activity inputs are held constant).**

Chapter 4. Industrial Processes and Product Use (IPPU)

4.17 Iron and Steel Production and Metallurgical Coke Production

Comment: Subchapter is Disjointed and Terms Need Defining

I find this subchapter to be somewhat disjointed. In its opening remarks, it would be best to explain that "pig iron" is the common, but unfortunate term used for what would be better described as "crude iron". Pig iron is really that (small fraction currently; a large fraction 50-100 years ago) subset of crude iron production that is actually poured into small molds to form "pigs". The current interchangeable use of "pig iron" for "crude iron" can lead to problems with the foreign literature/statistics. For example, some years ago, the USGS data on Turkish crude iron output was erroneously revised downwards from, if memory serves, c. 5 Mt/yr. to something like 250,000 MT/year, because the then country specialist (the late Phillip Mobbs) had found a Turkish Govt. reported data series for pig iron. What he had found was a longstanding series for "pik demir" (which is the iron cast into pigs), whereas what he should have (continued to have) used was the reported series for "ham demir" (crude iron). When the error was pointed out to Mr. Mobbs, he revised the data back to the larger number series.

Most of the CO_2 released in iron & steel production is from the production of crude iron; although the chapter does mention this here and there, the main impression is that the focus is on crude steel production.

In blast furnaces, the CO_2 largely comes from the use of coke and the carbonate flux (really, it's a slagging agent, although "flux" will suffice). The use of flux seems not to be dealt with except indirectly. Mention is made of a deduction (from Other Carbonate Uses) to avoid double-counting of the flux used in steel production, but in reality, you should say "...in crude iron production". It is the blast furnace that uses limestone and/or dolomite. Steel furnaces use LIME as a flux, and this use should not release any additional CO_2 (the manufacture of lime, of course, is dealt with in a separate chapter); most U.S. integrated plants, and all independent EAF plants, buy their lime from the lime industry.

In making crude iron in a blast furnace, you will consume c. 0.2 - 0.5 t of carbonate slagging agent (limestone and/or dolomite) per ton of crude iron produced, which would thus yield approx. 0.1-0.2 t of CO_2 per ton of iron; the net calculation (all sources) would be debited for carbon (c. 4%) remaining in the crude iron. Then the subsequent steel furnace will burn off most of this carbon in the crude iron feed; an EAF may burn some C-electrode to add carbon to the melt if it overburned the melt's carbon by mistake.

If you are going to mention the number (11) of iron and steel (integrated) complexes, it would be of interest to note that there were 21 active blast furnaces (only) in 2015 at these plants--a sad decline...

Section 24 (Iron and Steel Production) is introduced by talking about the minor stuff (sinter, DRI, pellets) rather than the major outputs of crude iron and crude steel.

In the first para of section 4-25; add "carbonate fluxes or slagging materials" to the list of inputs to the blast furnace.

In the 2nd para (line 12), fluxes appears as an input for steel production; again, for steel production, the flux is lime, not carbonate, and will not yield CO_2 in the steel furnace. The confusion is continued in lines 15-17 where carbonates are linked to steel manufacture instead of to crude iron production.

Table 4-29 would be more useful if you split the inputs in terms of those for crude iron production (blast furnace) from those for crude steel production (steel furnace).

Table 4-31 needs a data series for flux (slagging agent) consumption for the blast furnaces. It is unclear if any of this (carbonate) flux was put in the EAF and BOF sections; if so, it should be removed. The EAF and BOF flux of interest is lime. However, be aware that some data for "fluxes" for BFs includes silica sand (which is a flux, but yields no CO_2).

Response: **EPA has updated background descriptions to improve the explanation of current production processes and to clarify the use of the terms "pig iron" and "crude iron" in the upfront section of the source category text. This update is to reflect the iron and steel emissive processes, the status of the industry, and changes over the time series. For the current inventory (i.e., 1990 through 2016), EPA has not implemented updates to Table 4-31 to include slagging agent consumption for blast furnaces. EPA will need to assess available data and review appropriate emission factors per the 2006 IPCC Guidelines before including in future reports.**

Chapter 6. Land Use, Land Use Change and Forestry (LULUCF)

Comment: Chapter is Clear

We find the chapter to be clear, transparent, concise, understandable, and thoroughly documented. The basic methodology and data sources are sound and have remained mostly unchanged. EPA is using appropriate data for components of this chapter, and the forest inventory data which forms the basis for all forest carbon stock estimates is undergoing steady improvement with thorough scientific review.

Response: **EPA appreciates the commenter's feedback on clarity and transparency of Chapter 6 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.**

6.1 Representation of the US Land Base

Comment: Question about Availability of Citations

I hope the citations that are described as "in prep" are available to reviewers within the coming year? Especially on page A-207, Theoretical age class transition matrix, Wear and Coulston in prep.

Response: **Most of the references listed as in prep on page A-207 are published, the figure will be updated with the correct citations in the final Inventory published in April 2018.**

Comment: Question about FIA Data Table

I can appreciate the approach to not greatly update the inventories every year, and instead go to biennial reporting. It is a great deal of work to update the inventories.

My main comment is about Table 6-3. If FIA data are not used for forests in Alaska, (top part of table), it is hard to believe it is used in the croplands, grasslands, other lands, settlements, and wetlands for Alaska (bottom part of table, two dots in the FIA column). And how does this table relate to the presentation of the USGS numbers for Alaska? (See table 6-10).

Response: **The table (listed as 6-3 in Expert Review version) will be updated to indicate that FIA was used to determine land area for portions of Alaska. The chapter text already indicates this is the case. This table is not used directly in presentation of the USGS numbers for Alaska as shown in the Forest Land Remaining Forest Land section, but the outputs from the Land Representation analysis for Alaska is overlaid on the USGS spatially explicit estimates for Alaska to approximate the area of managed land and thus the "anthropogenic" emissions.**

Comment: Recommendation of a New Source

For US territories, a new publication has just been released based to a large degree on FIA data that states deforestation is not much of an issue in the islands. Would be worth a look, and perhaps citing. However, it doesn't include the most recent surveys from some of the islands. See Assessing Forest Sustainability in the Tropical Islands of the United States at the link below.

https://www.fs.fed.us/research/sustain/sustainability-reports.php#tabs-2

Response: **EPA will review the publication and when resources allow for inclusion of US Territories, EPA will utilize this to assist in developing estimates of GHG emissions/removals from these territories.**

6.2 Forest Land Remaining Forest Land

Comment: Parenthesis Needed
Typo: 6-31, line 1 – parenthesis missing after A-99

Response: **EPA has included the noted missing parenthesis.**

Comment: Change from 2015 Inventory Supported
We support the decision to move to a biennial compilation schedule, using land area data from the prior inventory (2015) for this report. This is a reasonable compromise to obtain accurate estimates while focusing efforts on other improvements, given the large area of the US land base and the relatively slow rates of change. This is well documented in the methodology sections.

Response: **EPA appreciates the commenter's feedback on the recent implementation of the biennial compilation process with the goal of directing resources to planned improvements for this source and enhancing the overall clarity and transparency of the methodology for Forest land Remaining Forest Land estimates in Chapter 6 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.**

Comment: Recent Improvements on Methodology are Successful
Recent improvements to the report methodology have made for a more comprehensive inventory, reflecting more land areas, all carbon pools, and providing better resolution on land area changes. Especially notable is the beginning of collection of inventory data for interior Alaska. When complete, this will add important information to the inventory.

Response: **EPA appreciates the commenter's feedback supporting the recent improvements to estimates for Forest land Remaining Forest Land in Chapter 6 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.**

Comment: Planned Improvements Supported
The planned improvements for Forest Land remaining Forest Land are well considered. We support the use of remotely sensed data for improving spatial and temporal scale of change data, following scientific review of methods. We also strongly support the dissemination of open source code for transparency in computations. More consistency in soil depth used for soil carbon reporting for land use changes is a worthwhile planned improvement.

Response: **EPA appreciates the commenter's feedback supporting planned improvements to estimates for Forest land Remaining Forest Land in Chapter 6 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.**

6.8 Wetlands Remaining Wetlands

Comment: Changes Needed to Synthesize Wetland Fluxes

It is clear that work remains to improve the inventory information on wetland changes. Identification of types of transition of lands into and from coastal wetland categories would be informative. In addition, some summarization of fluxes for the overall wetlands category would be beneficial; it is difficult to determine from the present format the total flux from wetlands remaining wetlands and lands converted to wetland as no summary table is presented. Fluxes for peatlands, vegetated wetlands, and un-vegetated wetlands and transitions among them are presented separately, making it difficult to synthesize information on overall wetland fluxes.

Response: **EPA appreciates the commenter's feedback on [additional] planned improvements to consider for Wetlands Remaining Wetlands in Chapter 6 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks. Improvements to the Wetlands section to better represent land use and transitions in the Wetlands category are planned for a future inventory, primarily by integrating the Coastal Change Analysis Program (CCAP) data into the land representation analysis. EPA will also evaluate how to improve the presentation of the Wetlands Section to provide a better summary of the fluxes from this chapter.**

6.10 Settlements Remaining Settlements

Comment: Clarity in Estimates are Underway

As noted in the report, improvements in distinguishing urban forest estimates from the rest of the forest inventory are underway, and will provide clarity in estimates pertaining to settlements remaining settlements as well as relevant transitions to and from the settlement category.

Response: **EPA appreciates the commenter's feedback supporting planned improvements for estimating Settlements Remaining Settlements in Chapter 6 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.**

6.10 Settlements Remaining Settlements – Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills

Comment: Description of Food Waste

Overall **-** I think that the methodology is clear and transparent and applaud EPA for the document's preparation.

Page 103: In describing the amounts of yard trimmings and food waste that are generated, I always use the word "estimated" as opposed to writing the text as if these quantities are definite. This is especially important in the case of food waste. The EPA considered food waste from sources that are defined as MSW only and does not include food waste that is generated at commercial food processing facilities (e.g., a factory that cans tomatoes or oranges). As such, the estimate of food waste to landfills is likely low.

Response: **EPA agrees that clarification is helpful and has edited the text to reflect that the values are estimated and not definite. Yard trimming and food scrap generation data are obtained from EPA's Advancing Sustainable Materials Management: Facts and Figures report, "Table 1. Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling of Materials in MSW". These MSW values include waste from residential, commercial, and institutional sources.**

Comment: Improvement for Methodology Needed

Page 104 – Methodology

This methodology captures food and yard waste present in MSW only. There are other sources. As noted above, in the case of food waste, there is commercial generation. In the case of yard trimmings, some debris from road construction is also disposed in dedicated landfills (I do not have detailed information but am told, for example, that the state Departments of Transportation operate “stump dumps” that received large trees.

Response: **EPA agrees, but has not identified data sources to quantify the food scraps from commercial sources or relevant debris from road construction for inclusion in estimating emissions/removals from landfilled, yard trimmings and food scraps, and have therefore not included these in the current estimates. EPA will continue to search for these data and add this to our list of planned improvements, noting that the commenter did not include any specific data sources to include these sources in the current Inventory report.**

Comment: Clarification of Decay Rates
Page 104 – Methodology

To clarify one item on the decay rates. The individual waste component decay rates that are given in de la Cruz and Barlaz (2010) for a bulk MSW decay rate of 0.04 can be readily adjusted to waste component decay rates for any other desired bulk MSW decay rate as follows:

Individual component decay rate at bulk decay rate of 0.03 = Individual component decay rate at bulk decay rate of 0.04 * 0.03/0.04

I think that EPA is aware of this but wanted to be sure.

Response: **EPA appreciates this feedback and will add this review to the planned future improvements the clarification on the decay rates and update the factors as appropriate following our review in future reports.**

Comment: Recommendation for Planned Improvements
Page 109 – Planned Improvements

It might be possible to consult with agronomists and get estimates of the mass of grass that grows per acre on residential lawns as a function of climate. This would provide a bottom up estimate of total grass generation that could be compared with the EPA methodology.

Response: **EPA will add commenter’s suggestion to the list of planned improvements to determine a total residential lawn grass generation for sake of comparison to our methodology as category-specific QC step per IPCC good practice to implement for future reports.**

Comment: Inconsistent Decay Rates
Table 6-76: The Decay Rates here do not match the values in de la Cruz and Barlaz. I think this is because the decay rates in Table 6-76 are weighted average rates across the US based on different regions with different bulk MSW decay rates. If I am correct, I suggest an explanatory note in Table 6-76.

Response: **EPA has included a note in Table 6-81, Section 6.10 of the Public Review version of the report stating that “the decay rates are presented as weighted averages based on annual precipitation categories and population residing in each precipitation category”.**

Comment: Attached Recommended Sources
Over the past several years, my group has published a number of papers on the biodegradability of wood. I am attaching those papers for your convenience. I do not think that they are necessarily of immediate use, but do think they provide some useful background for future work.

Response: **EPA appreciates this information and will review the papers in consideration with other planned improvements to consider how they can improve our methods for future estimates.**

Comment: Consistency Needed for Storage Factors
Finally, I agree with the comment that ultimately, we need to make the methane yields and C storage factors internally consistent. We have done this and adjusted methane yields accordingly in the following manuscript (Table S5).

Response: **EPA will review the paper (Hodge, K. L., Levis, J. W., DeCarolis, J. F. and M. A. Barlaz, 2016, "Systematic Evaluation of Industrial, Commercial, and Institutional Food Waste Management Strategies in the U.S," Env. Sci. and Technol., 50, 16, p. 8444 - 52) provided and will evaluate the potential to make adjustments to the inventory methodology for future inventory reports.**

Chapter 7. Waste

7.1 Landfills

Comment: Approval of Updated Approach for MSW Landfills
We have been very pleased with the cooperative effort among EPA and stakeholders to review and update the approach used to estimate greenhouse gas (GHG) emissions at MSW landfills and we look forward to continuing to work with you towards further improvements. The landfill sector strongly supports the Agency's efforts thus far to update the inventory, and particularly your decision to use Greenhouse Gas Reporting Program (GHGRP) data in the most recent inventory. We strongly support continued use of this data.

These data are more reliable and accurate for estimating nationwide emissions from MSW landfills. In previous comments on this issue, we explained why using GHGRP data is the preferred approach.

- The MSW landfill sector (Subpart HH) emissions data are significantly more detailed and up-to-date than the estimation approach used in previous GHG Inventories;

- Every MSW landfill reporting to Subpart HH is subject to annual validation via EPA review of submitted data – a level of scrutiny that does not occur in the GHG Inventory;

Each MSW landfill that reports under Subpart HH has a "designated representative," who must certify – under penalty of law – that the data submitted by the site are accurate and developed in accordance with regulatory requirements. These data are developed using consistent, EPA-approved methods, and are certified by reporters and independently quality-assured by EPA, which ensures transparent and reliable data for use in emissions estimates.

Response: **EPA appreciates the commenter's feedback supporting improvements applied for estimating emissions from Landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.**

Comment: The Scale-Up Factor for MSW Landfills

We thus recommend that EPA recalculate the scale-up factor using Option (a) and an adjusted WIP amount that is at least 60 percent lower than the amount assumed in the Agency's previous calculation. EPA's assessment of non-reporting MSW landfills shows that the GHGRP captures the vast majority of emissions from the MSW landfills and a scale-up factor of no greater than 5 percent would be far more appropriate for use in the Inventory.

Full Context: Recognizing that the GHGRP does not include every MSW landfill in the country – (MSW landfills that ceased taking waste prior to 1980 or have potential emissions less than 25,000 tons CO_2e) – we supported EPA's decision to use a scale-up factor to estimate emissions from non-reporting landfills in the 2017 Inventory. EPA calculated a scale-up factor of 12.5%, based on the percent difference between the 1990-2014 Inventory emissions and the GHG emissions as reported for 2010-2015 and back-casted emissions for 2005 to 2009. We were, however, concerned that the scale-up factor of 12.5% would be overly conservative, and recommended that a factor of 10% would be sufficient to avoid underestimating emissions. We also encouraged EPA to reassess an appropriate scale-up factor to more accurately account for non-GHGRP reporting landfills.

EPA has endeavored to do so by developing a draft list of MSW landfill facilities that do not report to the GHGRP by comparing the Agency's GHGRP database with the LMOP 2017 database and the Waste Business Journal (WBJ) 2016 database. This exercise has been fraught with difficulty due to the variety of facility names that may be associated with an individual landfill, the incorrect latitude and longitude values assigned to many landfills and the possible inclusion of non-MSW landfill sites in both the LMOP and WBJ datasets. EPA asked the landfill sector for assistance in reviewing the draft list.

Because the analysis of almost 1,800 landfill sites would be very time-consuming, the landfill sector focused its review on those landfills on the list with the greatest amount of waste-in-place. Waste-in-place is the primary variable for calculating potential emissions from a landfill. The landfill sector reviewed approximately a quarter of the sites on the draft list and found significant errors. Many of the sites were identified as reporting into the GHGRP, so their emissions were already captured. Other sites were misidentified as MSW landfills, and still other listed sites were duplicates and therefore accounted for multiple times.

The landfill sector[1] reviewed a total of 450 sites on the EPA's list of non-reporting MSW landfills. The below table summarizes the results of our review.

Summary of Review

450	**Total Sites Checked**
2	Duplicates
14	EXEMPT - NOT MSW landfills
287	Non-Reporting MSW landfills
147	Reporting-MSW landfills in GHGRP
3,057,855,595	EPA Total Forced WIP in tons for non-reporting sites
1,137,266,189	Industry Adjusted Forced WIP in tons for non-reporting sites
37.91%	% of Total

In adjusting the total forced WIP for remaining MSW landfills, the landfill sector removed only the WIP associated with non-MSW landfills (and those sites that are already reporting WIP and emissions through the GHGRP. Adjusting the WIP for this subset of landfills in the spreadsheet reduces the total WIP by more than 60 percent.

Developing an accurate list of non-reporting MSW landfills and the associated WIP is essential to both options the Agency has considered for calculating a scale-up factor.

a) The percentage difference in total waste-in-place between the non-reporting facilities and the GHGRP MSW landfill facilities; or
b) The percentage difference in net methane emissions between the non-reporting facilities and the GHGRP MSW landfills.

Using its draft list on non-reporting landfills, EPA determined that Option (a) yields a scale-up factor of approximately 11%, as shown in Table 1 of the October 16, 2017 EPA Expert Review memo. This value was determined from the estimated total waste-in-place for non-reporting facilities compared to facilities reporting to the GHGRP. To calculate GHG emissions for non-reporting facilities, 11% of the total GHGRP emissions for each year of the time series would be applied.

Option (b) yielded a scale-up factor of approximately 26%, as shown in Table 2. This value was determined from estimated methane emissions for the non-reporting landfills. EPA used the Inventory Waste Model (first order decay methodology) and estimated annual waste disposal data that excludes an average amount of C&D and inert waste, and the same default factors as applied in previous inventories for DOC, MCF, etc., and a 10 percent oxidation factor.

Leaving aside the fundamental flaws with the EPA list of non-reporting landfills, the landfill sector recommends that Option (a) is the more appropriate approach because waste-in-place data are readily available and are more reliable than modeled net emissions. Specifically, Option (a) relies on available waste acceptance data to determine waste-in-place for the non-reporting facilities and waste-in-place data reported under the GHGRP for MSW landfills reporting under Subpart HH. Option (b), in contrast, relies on the first order decay methodology, as well as many default factors that may not be appropriate across the country.

We thus recommend that EPA recalculate the scale-up factor using Option (a) and an adjusted WIP amount that is at least 60 percent lower than the amount assumed in the Agency's previous calculation. EPA's assessment of non-reporting MSW landfills shows that the GHGRP captures the vast majority of emissions from the MSW landfills and a scale-up factor of no greater than 5 percent would be far more appropriate for use in the Inventory.

[1] - SWANA members in state chapters across the country; major, private landfill owner/operators who are members of NWRA; SCS Engineers and Weaver Consulting, which conduct GHG Reporting for many public and private sites, and WM and Republic Services.

***Response*:** **EPA appreciates the commenter's feedback supporting planned improvements for estimating emissions from landfill in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. EPA also appreciates the effort undertaken by the landfill industry to review the list of landfills that do not report to the GHGRP and the attempt to remove reporting landfills and duplicates, as well as fill in missing waste-in-place and open/closure year data where available. Based on further review within EPA and industry input, EPA has revised the scale-up factor used in the emissions estimations for 2004-2016 in the time series from 12.5% to 9%. Please**

refer to the Recalculations Discussion in Section 7.1 of the Inventory text as well as the supporting memo "Methodological refinements as applied in the 1990-2016 estimates of U.S. greenhouse gas emissions from MSW landfills to account for emissions from facilities not reporting to the Greenhouse Gas Reporting Program" from Kate Bronstein and Meaghan McGrath of RTI International to Rachel Schmeltz of EPA/CCD, April 4, 2018 for more detail on the steps taken to refine the scale-up factor.

Comment: The Scale-Up Factor for MSW Landfills
1) Additional datasets to generate and/or refine a list of non-reporting landfills.

Both EPA and the landfill sector have spent considerable time attempting to create a useable database of non-reporting landfills based on EPA's LMOP and WBJ databases. There are no other datasets to evaluate. This effort has been difficult and time-consuming for many reasons, including problems in identifying non-reporting landfills, tracking down landfills with addresses but incorrect LAT/LONG coordinates and confirming that GHGRP, C&D, and industrial landfills are not in the non-reporting landfill database. Significant effort was undertaken by the landfill sector to review and revise the list of non-reporting landfills. With additional time, we believe we could further refine the list. However, our review to date of the Agency's database of non-reporting landfills has eliminated over 60 percent of the total waste-in-place used to calculate the Agency's initial scale-up factors of 11% and 26%. We recommend the Agency recalculate the scale-up factor using Option (a) and a reduced WIP amount that is at least 60 percent less than that used in the prior calculation.

Response: **EPA appreciates the commenter's feedback confirming that there are no additional datasets to use in informing the scale-up factor applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. EPA also appreciates the effort undertaken by the landfill industry to review the list of landfills that do not report to the GHGRP and the attempt to remove reporting landfills and duplicates, as well as fill in missing waste-in-place and open/closure year data where available. Based on further review within EPA and industry input, EPA has revised the scale-up factor used in the emissions estimations for 2004-2016 in the time series from 12.5% to 9%. Please refer to the Recalculations Discussion in Section 7.1 of the Inventory text as well as the supporting memo "Methodological refinements as applied in the 1990-2016 estimates of U.S. greenhouse gas emissions from MSW landfills to account for emissions from facilities not reporting to the Greenhouse Gas Reporting Program" from Kate Bronstein and Meaghan McGrath of RTI International to Rachel Schmeltz of EPA/CCD, April 4, 2018 for more detail on the steps taken to refine the scale-up factor.**

Comment: The Scale-Up Factor for MSW Landfills
2) How to handle landfills that "off-ramp" from the GHGRP.

The first reporting year for Subpart HH (and other subparts) was 2010, and the latest reporting year is 2016. To date, 16 landfills (out of 1137 in 2015) have met the criteria for exiting the GHGRP reporting requirements, representing merely 1.4% of the landfills reporting under Subpart HH. Given the very small number of landfills that have stopped reporting, we find it unnecessary and a very poor use of Agency resources to develop a new approach for accounting for these landfills' emissions. The potential effect of these emissions is tiny, particularly considering the revisions to the dataset of non-reporting sites, and the uncertainties and errors introduced using the first order decay model and non-representative DOC values. Further, EPA has the historical data for the "off-ramp" sites and most if not all the "off-ramp" sites are closed landfills where emissions will continue to decline over time.

Response: **EPA appreciates the commenter's assessment of the utility of developing an approach to account for emissions from landfills that have stopped reporting to the GHGRP because they met**

the "off-ramp" provisions (i.e. reported less than 15,000 metric tons of CO_2 equivalent for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent for 5 consecutive years). While the data reported by these facilities in previous reporting years is incorporated into the scale-up factor analysis, no separate approach has been developed. EPA will periodically assess the impact these off-ramping facilities may have on emissions estimates to ensure national estimates are as complete as possible.

Comment: The Scale-Up Factor for MSW Landfills
3) What is the best approach for applying a scale-up factor?

EPA is currently applying the same scale-up factor for 2005 to 2016, but is considering whether it would make more sense to apply a scale-up factor to blocks of time (e.g., 5 years), annually, and/or when GHGRP facilities off-ramp.

The landfill sector does not see the value in applying the scale-up factor at such a detailed level, given the significant reduction in the potential impact of non-reporting landfills to nationwide emissions, and the small number of landfills likely to either drop below the threshold for reporting or reach the Subpart HH threshold for reporting. This represents a poor use of the Agency's limited resources.

Response: **EPA appreciates commenter's input on the application of the scale-up factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.**

Comment: Degradable Organic Carbon (DOC)
Conclusion: Based on EREF's research, we urge EPA to update the DOC values to reflect significant changes in the amounts and types of organic materials being landfilled over the last several years. The values now in use are inaccurate and should not be used going forward. We request that EPA review and update the DOC values in the next version of the GHG Inventory.

Full Context: In 2016, the Environmental Research and Education Foundation (EREF) undertook a state-based study of DOC values for both MSW Only Landfills and Non-MSW Material going to MSW Landfills. The DOC guideline recommended by EPA for MSW Only Landfills is 0.31 and the recommended guideline for Non-MSW material going to MSW landfills is 0.20. As described below, these guidelines over-estimate the amount of organic waste deposited in landfills, which results in inaccurate estimates of landfill gas generation and methane emissions. We note that neither of the recommended DOC guidelines have been reviewed by EPA in many years, and we support EPA's view that it is time to update the DOC values.

EREF reviewed recent waste composition studies for MSW Only Landfills conducted by 13 states and confirmed that waste composition has and continues to change over time, as fewer organic materials are sent to MSW landfills. In fact, the EREF results show that the percent of the MSW-only stream that is organic waste ranged from 50.1% to 69.4%, with an average of 60.2% (Table 1).[2] EPA data also indicate that the fraction of organics going to landfills generally declined from 1994 to 2009. Quoting EREF:

Subsequent analyses were performed using both state characterization study data and EPA Facts and Figures data to compute DOC values for MSW (DOCMSW). An average DOCMSW of 0.184 was computed from the state study data, with values ranging from 0.142 – 0.209. All characterization studies had DOCMSW values significantly less than the default value of 0.31, which suggests this value is not representative of real-world conditions for MSW (Table 2; Figure 4). Analysis of U.S. EPA data … also results in a significantly lower DOCMSW value compared to the U.S. EPA guideline of 0.31, with

DOCMSW values ranging from 0.218 in 1994 to a minimum of 0.165 in 2011 (Figure 4; Appendix B). Both the state characterization studies and U.S. EPA Facts and Figures data independently suggest that a DOC guideline value of 0.31 for MSW is not representative of the landfilled MSW stream.

The use of a single DOC value as a guideline for all U.S. landfills makes the implicit assumption that waste composition does not change over time or due to location. The results presented here suggest these are not valid assumptions and that, collectively, the use of a static DOC value of 0.31 may lead to inaccurate estimates of landfill gas emissions for landfills that only accept MSW. Because this specific analysis is focused only on MSW materials, one would expect the inclusion of non-MSW materials going to a landfill to impact DOC estimates even more.[3]

With respect to Non-MSW going to MSW Landfills, EREF finds “a common assumption is that all waste materials entering MSW landfills consist only of MSW materials. As noted previously, MSWLFs rarely accept MSW exclusively. Rather, most MSWLFs (landfills in 45 states) are authorized to accept other Subtitle D wastes in addition to MSW.”[4] In addition, EREF notes:

Given that a third of incoming waste to MSWLFs consists of non-MSW materials, there is significant potential for non-MSW materials to impact the relative fraction of organics and degradable organic carbon (DOC) of the MSWLF waste stream.[5]

The amount and types of non-MSW Subtitle D organic wastes impact the DOC value for the landfilled waste since it consists of both MSW and non-MSW streams. This combined DOC value (DOCSubD) incorporates degradable organic carbon from all Subtitle D wastes accepted at MSWLFs (both MSW and non-MSW). … State waste characterization studies were used to estimate the relative fraction of each organic constituent for C&D and industrial waste … and DOC for each waste type was calculated using Equation 1b. Based on this analysis the DOCSubD value of landfilled waste is 0.161 (Table 6).”[6]

EREF also highlights that the DOCSubD value is lower than the guideline value of 0.20 for bulk waste. It is also lower than the average DOCMSW value of 0.184 computed in the prior section, indicating the inclusion of non-MSW decreases overall DOC. Using the same approach as for the DOCMSW analysis, state-specific organics content and DOCSubD values for all fourteen states with sufficient data were determined and presented in Table 7, below. The results, all for 2013, highlight differences in DOCSubD based on locale and suggest the use of a static 0.20 guideline for bulk waste may lead to inaccurate estimates of methane generation and emissions, especially in some areas.[7]

Thus, EREF concludes as follows:

The average computed DOC value for MSW using state data was 0.184, or roughly three-fifths of the MSW guideline value. The average computed DOC value for bulk waste using state data was 0.161, or roughly four-fifths of the bulk waste guideline. This analysis suggests that the U.S. EPA’s guideline DOC values of 0.31 for MSW-only landfills and 0.20 for facilities accepting non-MSW Subtitle D wastes overestimate DOC at these landfills and may result in inaccurate estimates of landfill gas generation and methane emissions.[8]

Based on this review of the DOC values for MSW landfills, the landfill sector concludes that the long-standing DOC values developed in the past are inaccurate and are likely to over-estimate both landfill gas generation and methane emissions. The data provided by EREF confirms that two trends are driving the changes at MSW landfills. First, many MSW landfills are handling less organic matter now, and this trend is anticipated to continue due to state and local organics diversion goals, and second, the increase of Subtitle D non-MSW waste disposed has altered the DOC for all waste deposited in MSW landfills.

Based on EREF's research, we urge EPA to update the DOC values to reflect significant changes in the amounts and types of organic materials being landfilled over the last several years. The values now in use are inaccurate and should not be used going forward. We request that EPA review and update the DOC values in the next version of the GHG Inventory.

[2] - Staley, B.F. and Kantner, D.L., Estimating Degradable Organic Carbon in MSW Landfills and the Impact of Non-MSW Materials, EREF – Environmental Research and Education Foundation, 2016, Table [1] p. 4.
[3] Ibid. pp. 6 - 7
[4] Ibid. p. 8
[5] Ibid. p. 10
[6] Ibid. p. 11
[7] Ibid. p. 12
[8] Ibid. p. 13

***Response:* As stated in the Planned Improvement section of Section 7.1 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, the Inventory currently uses one value of 0.20 for the DOC for years 1990 to 2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide).**

Comment: The k Factor (Methane Generation Rate Constant)
On page 25 of the U.S. Greenhouse Gas Inventory: Update on Methodology Improvement for MSW Landfills,[9] EPA notes that it is using k-values based on climate. Estimation of the CH_4 generation constant (k) is a function of a variety of factors, including moisture, pH, temperature, and other environmental factors, and landfill operating conditions."[10] For many years, EPA has used three k values, disaggregated by climate: 0.02 [dry climate], 0.038 [moderate climate], and 0.057 [wet climate].

We are concerned that these k-values are outdated and rife with uncertainty, as confirmed by the Draft AP 42.2.4 Municipal Solid Waste Landfills, which states:

There is a significant level of uncertainty in Equation 2 and its recommended default values for k and Lo. The recommended defaults k and Lo for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH_4 emissions that ranged from ~30 to 400% of measured values and had a relative standard deviation of 0.73 (Table 2-2). The default values for wet landfills were based on a more limited set of data and are expected to contain even greater uncertainty.[11]

As noted above, the landfill sector has previously highlighted the significant issues with the k values used in the Draft AP-42 Section 2.4: Municipal Solid Waste Landfills. In fact, EPA has never finalized AP-42 for MSW landfills, despite the k-value issues identified by EPA in both AP-42 and the Background Information Document. With uncertainties in CH_4 emissions ranging from -30% to 400% under EPA's assessment of the LandGEM model, it is difficult to take these data seriously. For this reason, we again urge EPA to review and resolve the significant problems in the k value data set.

[9] U.S. EPA, U.S. Greenhouse Gas Inventory: Update on Methodology Improvements for MSW Landfills, August 16, 2017.
[10] U.S. EPA, Draft AP 42.2.4: Municipal Solid Waste Landfills, October 2008, p. 2.4-6.
[11] Ibid.

Response: **As stated in the Planned Improvement section of Section 7.1 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, in a future Inventory cycle, EPA will review the k values for the three climate types (dry, moderate, and wet) against new data and other landfill gas models, and how they are applied to the percentage of the population assigned to these climate types. EPA will also assess the uncertainty factor applied to these k values in the Waste Model. A 30 percent uncertainty factor is applied to each k value in the Monte Carlo analysis, which is consistent with that recommended by the IPCC (2006).**

Comment: The 10 Percent Oxidation Factor
For the period 1990 – 2004 in the inventory time series, a national estimate of methane generation and emissions are calculated using a combination of secondary data sources that detail the annual quantity of waste landfilled and the annual quantity of methane recovered from facilities with landfill gas collection and control systems. EPA applies a 10% oxidation factor to all facilities for the years 1990 to 2004.

We understand that EPA is considering revisions to the value of the oxidation factor and possibly including two oxidation factors: one for waste disposed at facilities with landfill gas collection and control systems (GCCS), and the other for landfills without GCCS. EPA acknowledges that the Agency has not developed a way of assigning a percentage of waste disposed in landfills with gas collection or without for those years.

While assigning different methane oxidation values to landfills with and without gas collection systems may seem to be a valid concept, that one site variable should not be applied to all sites in the inventory universe as THE defining characteristic affecting methane flux and oxidation. Other site-specific landfill attributes are important in assessing methane oxidation potential (e.g., WIP, modeled CH_4 generation, cover area and cover type). Sites with gas collection might have lower methane flux into the cover and thus would be expected to have higher rates of oxidation due to this lower flux. However, applying this one characteristic to all landfills in the Inventory without respect to their other site-specific attributes will not provide a valid, nationwide analysis. Many sites in the Inventory are small or older sites with low gas generation rates and low methane flux. They would still be expected to have oxidation rates that exceed 10% even without gas collection systems. So, the information needed to provide an accurate estimate of methane oxidation goes beyond simply knowing whether the site employs gas collection or not.

Response: **EPA appreciates commenter's input on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux. The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: The 10 Percent Oxidation Factor
1) Available data sources to address trends in installation of landfill gas collection systems.

The landfill sector is not aware of sources that would provide information on the extent of landfill gas collection within the industry or the trends in gas system installation outside of the reporting landfills in the GHGRP. The EPA LMOP dataset only indicates whether a landfill has a gas collection system, but does not note the date of installation or expansion.

Response: **EPA appreciates commenter's input and takes note that the commenter is not aware of any data sources to address trends in installation of landfill gas collection system. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: The 10 Percent Oxidation Factor
2) Appropriate oxidation factors for landfills with and without landfill gas collection systems.

The landfill sector does not think that it is appropriate to assign oxidation factors to a landfill based solely on whether it operates a GCCS. As explained above, other site-specific landfill attributes, such as WIP, type and extent of cover and modeled methane generation are also important factors in assessing potential methane oxidation. Developing an accurate estimate of methane oxidation is significantly more complicated than relying on whether the landfill has a gas collection system.

Response: **EPA appreciates commenter's input on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016 and that the existence of a GCCS is not the sole factor in estimating the amount of methane oxidation. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: The 10 Percent Oxidation Factor
3) Appropriate oxidation factor if only one factor is used for all waste disposed between 1990 and 2004.

The existing Subpart HH treatment of methane oxidation requires knowledge of landfill attributes to calculate methane flux and assess the corresponding methane oxidation value based on the bin approach. The bin approach is a conservative estimate based on 800 field estimates of oxidation for a range of methane flux results, as provided in the SWICS addendum and RTI memo. It is our view that EPA should use the flux based oxidation factor, as it could be applied more broadly than the current application in Subpart HH and is the most defensible approach.

Response: **EPA appreciates commenter's input on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: The 10 Percent Oxidation Factor

4) Methane leakage from cracks and fissures in the cover, and whether to apply a leakage factor for landfills when assigning oxidation rates.

We find it very hard to understand how the Agency could know or even estimate the extent of cracks and fissures at landfills on a site-specific basis or more broadly on a nationwide, inventory basis. Furthermore, there is no proven or accepted method to determine leakage from cracks and fissures. The reason is that the flux through the cover (and the fraction oxidized) is dependent upon the interactions among many factors, including soil and physical properties of cover such as gas porosity; organic content and moisture; microbiological factors such as temperature and substrate availability; and the presence or absence of a gas collection system. In a 2011 paper in Environmental Science & Technology, researchers looked at the surface air methane 13C value at 20 landfills and found that the oxidation percentage was 36%, as compared to an oxidation rate of 37% measured in surface chambers. Based on this result, methane emitted via cracks and fissures did not appear to be a significant factor, and the presence of cracks and fissures did not necessarily result in higher emissions or lower oxidation.

The landfill sector does not support the development of additional leakage factors for landfills because leakage is already reflected in the calculated flux rates. The higher the flux rate the lower the oxidation rate. We think it is neither valid, nor reasonable to develop leakage factors beyond the GHGRP flux rate calculations for determining an appropriate methane oxidation rate, without extensive scientific support.

***Response:* EPA appreciates commenter's lack of support for developing an additional leakage factor when assigning oxidation rates as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: Data Change for Material Discarded

On page 7-12, Table 7-3 represents Material Discarded. These numbers should add up to 100%. They do for 1990, but not for any of the other years. These amounts are off significantly enough that it is unlikely due to rounding.

- 1990 – adds to 100%
- 2005 – totals 98%
- 2010 – totals 93.8%
- 2011 – totals 112.2%
- 2012 – totals 91.3%
- 2013 – totals 92.7%
- 2014 – totals 93.6%

Also, it seems to me that this table should follow Table 4 of EPA's Advancing Sustainable Materials Management: Facts and Figures 2014 which represents materials landfilled. Rather, it states that it also includes discards that went to WTE facilities. That being said, the 1990 column matches EPA's SMM Table 4.

***Response:* EPA appreciates the commenter's detailed review of the tables in the landfills section of Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. EPA has**

reviewed and revised the numbers in and footnotes to the table titled "Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2014" based on these comments.

Comment: Additional Information for Text
Page 3, Line 22: Another factor is the relatively low price being paid for natural gas

Response: **EPA acknowledges that the fluctuation in natural gas pricing may be a factor in the feasibility of LFGTE projects and will investigate this and other potential factors that are impacting the development of new LFGTE projects for inclusion in a future Inventory report, as appropriate.**

Comment: Scale-up Factor Needs Clarification
Page 5, Line 27: With respect to the scale-up factor, this is a challenging issue. See the Appendix of the attached article by Powell et al where they try to address the same issue. They provide an estimate of MSW in landfills not obligated to report.

The method used by EPA is a little hard to follow. One factor that I want to be sure to consider is that the landfills not captured in various databases are likely smaller landfills. As such, scaling should be done on the basis of MSW buried and not on the basis of an estimate of the number of missing landfills. I also think it important to recognize that the estimates are not likely to be within 12.5% anyway so I do not think that too much significance should be placed on the factor actually used. Using 12.5% as opposed to 10 or 12 implies more significance than is appropriate.

Response: **EPA appreciates the commenter's input and the article reference provided (Powell, J., et al., 2015, "Estimates of Solid Waste Disposal Rates and Reduction Targets for Landfill Gas Emissions," Nature Climate Change, 21 September 2015). EPA will review the article and evaluate the potential to make adjustments to the inventory methodology.**

Please refer to the supporting memo "Methodological refinements as applied in the 1990-2016 estimates of U.S. greenhouse gas emissions from MSW landfills to account for emissions from facilities not reporting to the Greenhouse Gas Reporting Program" from Kate Bronstein and Meaghan McGrath of RTI International to Rachel Schmeltz of EPA/CCD, April 4, 2018 for more detail on the steps taken to refine the scale-up factor including use of the Waste Business Journal database as one of the sources for this work. EPA agrees that landfills not captured in the databases are likely small and EPA has pursued the path of basing our scale-up factor on WIP, rather than numbers of landfills not reporting to the GHGRP.

Comment: Discussion with Flare Vendors Suggested
Page 8 – lines 7-18: In evaluating appropriate destruction efficiencies for flares, I encourage EPA to discuss with some flare vendors as they may have unpublished data that is useful. The values in AP-42 are so old that there should be an opportunity for additional data to be considered.

Response: **EPA appreciates commenter's input. EPA acknowledges that the AP-42 document references is old and potentially outdated. EPA will investigate revisions to the destruction efficiencies for flares in a future Inventory report, as appropriate.**

Comment: Methane Oxidation
If using one value for all landfills from 1990-2004, I think 10% is biased low. Some of these landfills had good collection and control, however, I do not have a good basis for suggesting what the oxidation factor should be. One compromise might be to allow 20% for landfills with gas collection.

I do not suggest the application of a leakage factor to account for cracks and fissures. While mechanistically appropriate, there is so much uncertainty in the leakage factor as well as the methane oxidation rate that adding another factor with a highly uncertain value does not improve estimates of methane oxidation.

Response: **EPA appreciates commenter's lack of support for developing an additional leakage factor for the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. As stated in the Planned Improvement section of Section 7.1 of the Inventory, EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approached used in the GHGRP (e.g., 10 percent, 25 percent, 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.**

Comment: Use of LMOP database
I think that considerable caution is needed. The LMOP database is self-reported with no quality control. In addition, it is not updated when a gas to energy project changes.

Response: **EPA appreciates commenter's input. Please refer to the supporting memo "Methodological refinements as applied in the 1990-2016 estimates of U.S. greenhouse gas emissions from MSW landfills to account for emissions from facilities not reporting to the Greenhouse Gas Reporting Program" from Kate Bronstein and Meaghan McGrath of RTI International to Rachel Schmeltz of EPA/CCD, April 4, 2018 for more detail on the steps taken to refine the scale-up factor including use of the LMOP database as one of the sources for this work.**

LMOP is a voluntary partnership program designed to help reduce methane emissions from landfills by encouraging the recovery and use of landfill gas (LFG) energy as an energy resource. To support its mission, LMOP collects information from its Partners (using its approved ICR, No. 1849.07; OMB Control Number 2060-0446) on their landfill gas energy project development activities as well as basic physical and operational data about municipal solid waste landfills. LMOP has processes and procedures in place to ensure the data collected is consistent and accurate.

For example, LMOP provides instructions to Partners on how to collect and report data to EPA. Once data is submitted, program staff and federal contractor staff review and discuss. Any data inconsistencies or other issues identified are resolved through follow-up correspondence with the Partner company representative to obtain needed corrections or clarifications. Data that has been reviewed and verified is then entered into the LMOP Landfill and LFG Energy Project Database (LMOP Database). In addition to Partner reported data, LMOP compiles data from additional publicly available sources such as news articles, press releases, reports, presentations, and organization websites; state websites, databases, reports, and permits; and EPA's Greenhouse Gas Reporting Program. For these data sources, LMOP follows the same review processes as outlined above to ensure data is consistent and accurate.

Comment: DOC
Without question, the DOC of waste entering landfills has changed since 1990 and continues to change as more fiber is recycled and the residual MSW is enriched in food waste as well as non-recyclables. I would like to see the DOC vary annually or perhaps in 5 year increments to recognize that the DOC is changing. More broadly, EPA has estimates of the methane yield for individual waste components and estimates of waste composition. I would prefer to use these data to calculate L0 and DOC. The L0 based

on AP-42 results in an empirical value that gives the best curve fit. However, this value, while referred to as the methane production potential, in fact has lots of other factors embedded given the empirical nature of the LandGEM model for which it is used.

Response: **As stated in the Planned Improvement section of Section 7.1 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, the Inventory currently uses one value of 0.20 for the DOC for years 1990 to 2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide).**

Comment: Annex Table A-2
I have done extensive analysis of decay rates in consideration of landfill gas collection efficiencies. I have attached 2 manuscripts that suggest that higher decay rates and lower values of L_0 may be more appropriate.

Response: **EPA will review the manuscripts provided (Wang, X. et al. 2015 "Characterization of Uncertainty in Estimation of Methane Collection from Select U.S. Landfills," Env. Sci. and Technol., 49, p. 1545-1551 and Wang, X., et al. 2013"Using Observed Data to Improve Estimated Methane Collection from Select U.S. Landfills," Env. Sci. and Technol., 47, p. 3251-3257) and evaluate the potential to make adjustments to the inventory methodology for future inventory reports.**

Comment: MCF and open dumps
I would assume that all open dumps in the U.S. were deep. This is because our populations are so high. I think of shallow open dumps as applicable to rural areas in underdeveloped countries.

Response: **For the Final Inventory report, the EPA will revise the text to revise the word "dump" to match the specific solid waste disposal sites (SWDS) category included in the IPCC 2006 Guidelines and modeled. While there are categories for unmanaged shallow (MCF of 0.4) and deep (MCF of 0.8) SWDS in the waste model, the EPA does not apportion any percentage of waste being disposed in these categories at any point since 1940. From 1940 to 1979, a portion of the waste disposed is assigned to the uncategorized SWDS category (with an MCF of 0.6). The EPA has not found sources documenting the depth of the unmanaged sites across the US, and therefore models waste disposed in the IPCC's uncategorized SWDS category.**

Comment: Additional Source Attached
I have also attached some work we did for EPA in support of the WARM Model.

Response: **EPA will review the work done in support of the WARM model (Levis, J. and Barlaz, M., 2014, "Landfill Gas Monte Carlo Model Documentation") and will evaluate the potential to make adjustments to the inventory methodology section for future inventory reports.**

7.2 Wastewater Treatment

Comment: Suggestion for Methodology of Characterizing Production of Pulp and Paper Sector
NCASI has previously submitted comments on some of the parameters used by the agency (see Supporting Material), and offers the following input.

Production. EPA continues to characterize production of the pulp and paper sector as the sum of woodpulp production plus paper and paperboard production, based on data from the Food and Agriculture Organization of the United Nations (FAO). As NCASI has commented in prior years, summing wood pulp, paper, and paperboard production results in double counting, because the majority of wood pulp production is used to produce paper and paperboard at integrated mills (an integrated mill includes both pulping and papermaking at the same facility, with a single wastewater treatment system). Therefore, production statistics used by EPA to represent the pulp and paper sector are too high, resulting in exaggerated estimates of pulp and paper industrial wastewater methane emissions.

As we have suggested before, a more appropriate method for characterizing total pulp and paper sector production would be to sum paper production, paperboard production, and market pulp production. The American Forest and Paper Association (AF&PA) publishes this information annually in its Statistical Summary reports, which are submitted each year to the US Library of Congress, and which EPA has cited as a source of information used to update industry wastewater generation rates.

Response: **EPA thanks the commenter for their input on the accuracy of estimating emissions from industrial wastewater treatment in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. EPA is in continued discussions with NCASI to evaluate the availability of more accurate data for use in revising the factors used to estimate emissions from wastewater treatment at pulp and paper manufacturing facilities.**

Comment: Average Outflow
EPA characterizes wastewater generation per ton of production based on water discharge statistics from AF&PA Sustainability Reports. These are the most current and relevant data for this characterization, and NCASI submits no comments on this use other than to emphasize that the agency should ensure it is using the most current version of the AF&PA Sustainability Report.

Response: **EPA thanks the commenter for their input on the accuracy of estimating emissions from industrial wastewater treatment in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. EPA is in continued discussions with NCASI to evaluate the availability of more accurate data for use in revising the factors used to estimate emissions from wastewater treatment at pulp and paper manufacturing facilities.**

Comment: Organic Loading in the Outflow
EPA characterizes the organic load in untreated wastewater using a legacy value of 0.4 gram BOD per liter of untreated effluent and a multiplier of 2 to convert from BOD to COD. NCASI has very limited data on untreated effluent organic load. Therefore, until additional data are available, we cannot suggest an alternative value.

Response: **EPA thanks the commenter for their input on the accuracy of estimating emissions from industrial wastewater treatment in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. EPA is in continued discussions with NCASI to evaluate the availability of more accurate data for use in revising the factors used to estimate emissions from wastewater treatment at pulp and paper manufacturing facilities.**

Comment: Production Statistics for Pulp and Paper Sector are Inaccurate
On page A-9, lines 2-5 of Annex 3.14 to the draft inventory, EPA outlines how pulp and paper industry production data used to estimate the sector's industrial landfill methane emissions are derived (by summing wood pulp, paper, and paperboard production data from FAO). As indicated above, this approach results in double counting because the majority of wood pulp production is used to produce paper and paperboard at integrated mills. Therefore, production statistics used by EPA to represent the

pulp and paper sector are too high, resulting in exaggerated estimates of pulp and paper industrial landfill methane emissions.

In summary, the agency's use of FAO statistics overstates the pulp and paper industrial sector's production by double counting pulp used to produce paper and board at integrated mills, which in turn results in estimates of pulp and paper sector industrial wastewater treatment and industrial landfill methane emissions being far too high. The agency should use production data from AF&PA's Statistical Summary reports to avoid this double counting. This will result in more accurate characterization of industrial wastewater treatment and industrial landfill methane emissions from this sector.

Response: **EPA thanks the commenter for their input on the accuracy of estimating emissions from industrial wastewater treatment in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. EPA is in continued discussions with NCASI to evaluate the availability of more accurate data for use in revising the factors used to estimate emissions from wastewater treatment at pulp and paper manufacturing facilities.**

Annex 3: Methodological Descriptions for Additional Source or Sink Categories

Annex 3.14 Methodology for Estimating CH_4 Emissions from Landfills

Comment: Additional Information Attached

Annex Table A-2: I have done extensive analysis of decay rates in consideration of landfill gas collection efficiencies. I have attached 2 manuscripts that suggest that higher decay rates and lower values of L0 may be more appropriate.

Response: **EPA will review the manuscripts provided (Wang, X. et al. 2015 "Characterization of Uncertainty in Estimation of Methane Collection from Select U.S. Landfills," Env. Sci. and Technol., 49, p. 1545-1551 and Wang, X., et al. 2013 "Using Observed Data to Improve Estimated Methane Collection from Select U.S. Landfills," Env. Sci. and Technol., 47, p. 3251-3257) and evaluate the potential to make adjustments to the inventory methodology for future inventory reports.**

Appendix A: List of Reviewers and Commenters

EPA distributed the expert review chapters of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016* to a list of 177 expert reviewers across all sectors of the Inventory. The list below includes names of those expert reviewers who submitted comments as part of the Expert Review Period.

- Hendrick G. van Oss – U.S. Geological Survey
- Kerry Kelly - Waste Management, Republic Services, National Waste & Recycling Association, Solid Waste Association of North America, SCS Engineers, and Weaver Consulting Group
- Anne Germain - National Waste & Recycling Association
- Morton Barlaz - NC State University - Department of Civil, Construction, and Environmental Engineering
- David H. Lax - American Petroleum Institute
- Pamela Lacey - American Gas Association
- Brad Upton - National Council for Air and Stream Improvement, Inc.
- Linda S. Heath - USDA Forest Service
- Stephen Prisley - National Council for Air and Stream Improvement, Inc.
- Morton Barlaz - NC State University - Department of Civil, Construction, and Environmental Engineering

Note: Names of commenters are listed in no particular order.

Appendix B: Dates of review

- Energy, Industrial Processes and Product Use (IPPU), and Waste: October 16 – November 14, 2017
- Supplemental Energy (Mobile Sources, CH_4, N_2O updates): October 31 – November 14, 2017
- Agriculture: October 19 – November 17, 2017
- Land Use, Land Use Change and Forestry (LULUCF): October 20 – November 17, 2017

Appendix C: EPA Charge Questions to Expert Reviewers

To facilitate expert review and indicate where input would be helpful, the EPA included charge questions for the Expert Review Period of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016* report. EPA also noted to expert reviewers that while these charge questions were designed to assist in conducting a more targeted expert review, comments outside of the charge questions were also welcome. Included below is a list of the charge questions by Inventory chapter.

Energy

General Questions

1. Please provide your overall impressions of the clarity and transparency of the Energy chapter.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Energy chapter.

CO_2 from Fossil Fuel Combustion

1. Please provide your overall impressions of the clarity of the discussion on trends in CO_2 emissions from fossil fuel combustion. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity.
2. Data for energy use in U.S. Territories comes from the International Energy Statistics provided by the Energy Information Administration (EIA). At the time of this 1990-2016 expert review draft Inventory, this source has data only through 2014, the data for years 2015 and 2016 are proxies in the Inventory. Are there other sources of U.S. Territory energy use that could be used?
3. Facility-level combustion emissions data from EPA's Greenhouse Gas Reporting Program (GHGRP) are currently used to help describe the changes in the industrial sector energy use. Are there other ways in which the GHGRP data could be used to help better characterize the industrial sector's energy use? Are there ways the industrial sector's emissions could be better classified by industrial economic activity type?
4. Electricity data is allocated between economic sectors based on electricity sales data provided by the industry through EIA reports. The data for electricity used in transportation only includes electricity used for railroads and railways. As a planned improvement, we will look into the possibility of breaking out electricity used to charge electric vehicles and report that electricity use under the transportation sector. Are data available on electricity used for battery electric and plug-in hybrid electric vehicle charging that could be used for this analysis?
5. Are you aware of any newer/updated carbon content coefficients, emission factors, or research we should be considering?

CH_4 and N_2O from Stationary Combustion

1. The CH_4 and N_2O emission factors for electric power sector are based on a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. The emission factors are primarily taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Are there other more U.S. specific CH_4 and N_2O emission factor data sources that could be utilized?
2. In the 1990-2016 expert review draft Inventory, EPA adjusted the CH_4 and N_2O emission factors for combined cycle natural gas units in the electric power sector to use EPA's Compilation of Air

Pollutant Emission Factors, AP-42, instead of the emission factors presented in the 2006 IPCC Guidelines. Are you aware of CH_4 and N_2O emission factors that have been developed more recently than the AP-42 factors that are as comprehensive (if not more)?

Carbon Emitted from Non-Energy Uses of Fossil Fuels

Please provide your overall impressions of the clarity of the discussion on Carbon Emitted from Non-Energy Uses of Fossil Fuels. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity especially in regards to links with the IPPU chapter.

Mobile Sources

1. Please provide your overall impressions of the clarity and transparency of the proposed mobile source updates.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the proposed mobile source updates.

Methodological Updates in Response to Changes to FHWA's Gasoline Consumption Estimation Models

Underlying data sources

As discussed EPA currently uses EIA data to represent total gasoline use and FHWA data to represent "Transportation" Sector gasoline use. The difference between the two is allocated to the "Commercial" and "Industrial" sectors for the Inventory. Primarily EPA used the FHWA Table MF-21 to determine overall Highway gasoline use but there are other sources available including FHWA Table MF-27 as well as FHWA Table VM-1 (which is used to determine fuel use by vehicle type).

1. Why are there differences in the different sources? Is FHWA Table MF-21 the best source of Highway gasoline use?
2. Why are there historic differences in FWHA Table MF-21 and MF-27 data? For the most recent years the MF-21 and MF-27 data match up, except for 2014, will the MF-21 data for 2014 be updated?
3. Are there other data sources we should be considering?

Proposed update:

The proposed update plans to adjust the gasoline consumption for the lawn & garden and recreational vehicle non-road categories. However, as shown in the tables above there were also changes to the other non-road categories in Table MF-24 in 2015.

1. Should the proposed update include adjustments to other non-road categories in table MF-24 (e.g., industrial and commercial)? If so, how should adjustments be made (e.g., use of EPA's NONROAD model data)?
2. How far back should the backcasting go? Should data back to 1990 be updated or only back to the previous FHWA of-road update?
3. Are there other approaches to backcast changes in gasoline use that EPA should consider (e.g., simple ratios)?

Other changes:

Currently "Transportation" sector gasoline use includes highway and recreational boat categories.

1. Is this an appropriate representation of "Transportation" sector? Should other categories be included here (e.g., recreational vehicles)?

Historically, CH_4 and N_2O emissions from non-road sources have been based on data from EPA's NONROAD model for different categories of non-road sources. These totals did not always match the totals from the FHWA MF-24 categories used in the CO_2 calculations.

2. Should these estimates be made more consistent? If so how? What are the main differences between the FWHA non-road calculations and EPA NONROAD model results?
3. Generally, are there other updates or changes we should consider for allocation of gasoline use to different source categories?

Industrial Processes and Product Use (IPPU)

General

1. Please provide your overall impressions of the transparency of the IPPU chapter.
2. Please provide any recommendations of improvements that EPA can consider to improve the completeness and/or accuracy of the IPPU chapter.
3. For the source categories included in the expert review draft, is the state of the industry current and accurately described? Are there technologies, practices, or trends that EPA should consider?

Source Specific

1. With the inclusion of a new IPPU source category, EPA requests feedback on the overall chapter text, assumptions and information on the state of the industry for the following category:
    a. Caprolactam, Glyoxal and Glyoxylic Acid Production
2. Please provide input on:
    a. Data sources and industry information on production of calcium carbide.
    b. Data on carbonate use in non-metallurgical magnesium production.
    c. Data on carbonate use in the production of ceramics.
    d. Recent/alternative production statistics for various N_2O product use subcategories listed within the Nitrous Oxide from Product Uses source chapter.
3. The EPA seeks comments on assumptions applied to determine the split between primary and secondary zinc production based on U.S. Geological Survey national totals. Are other options/data sources available to distinguish between process production totals?

Agriculture

General

1. Provide your overall impressions of the clarity and transparency of the Agriculture chapter.
2. Provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Agriculture chapter.
3. Provide feedback on the methodologies and activity data used to estimate emissions for categories within the Agriculture chapter.
4. Some categories in the Agriculture chapter have used surrogate methods to extend the emissions time series that are different from the methods used to estimate emissions during the earlier portion of the time series. These include Enteric Fermentation, Manure Management, Rice Cultivation, Agricultural Soil Management and Field Burning of Agricultural Residues. Please provide your input on the surrogate methods used to extend the time series for these categories.

Source Specific

1. For the Manure Management source category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider? Especially:
    a. Are the regional waste management system data used in the inventory (from USDA data sources) representative of actual observed waste management systems throughout the country?
    b. Are the trends observed in the inventory waste management system data over time representative of the trends observed in the industry?
2. The Manure Management source category relies on national/regional livestock production and management data for calculating emissions estimates. Are there other data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    a. Waste management system data
    b. Maximum methane producing capacity
    c. Volatile solids and nitrogen excretion rates
    d. Measured emission estimates (by waste management system) to help refine estimates of methane conversion factors
3. For the Enteric Fermentation source category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider?
4. The Enteric Fermentation source category relies on national/regional livestock production, diet and management data for calculating emissions estimates. Are there other data sources or methods that EPA should be aware of and consider in the calculating these emissions? Especially for:
    a. Dry matter/gross energy intake
    b. Annual data for the DE, Y_m, and crude protein values of specific diet and feed components for foraging and feedlot animals
    c. Monthly beef births and beef cow lactation rates
    d. Weights and weight gains for beef and dairy cattle
    e. Given the challenges in characterizing dairy diets, are there better methodologies we could be using to estimate DE for dairy? If so, what would you recommend, and what sources should be used?
5. Are you aware of other datasets or products that could be used to inform the management activities influencing soil N_2O emissions for Cropland or Grassland?
6. Are there management activities that would have a significant impact on soil N_2O emissions and are not currently addressed in the analysis for Cropland and Grassland?

Land Use, Land-Use Change, and Forestry (LULUCF)

General

1. Provide your overall impressions of the clarity and transparency of the LULUCF chapter.
2. Provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the LULUCF chapter.
3. Provide feedback on the methodologies and activity data used to estimate emissions for categories within the LULUCF chapter.
4. As noted in the Introductory section above, some categories in the LULUCF chapter have used surrogate methods to extend the emissions time series and are different from the methods used to estimate emissions during the earlier portion of the time series. Please provide your input on the surrogate methods used to extend the time series for these categories.

Source Specific

1. Are you aware of other datasets or products that could be used to inform the Land Representation analysis?
2. Are you aware of other datasets or products that could be used to inform our understanding of the current and past management activities for Cropland, Grassland or Settlements?
3. Are there other management activities that would have a significant impact on carbon stock change estimates for soils and are not currently addressed in the analysis for Cropland, Grassland or Settlements?
4. For the Yard Trimmings and Food Scraps category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider?
5. For the Yard Trimmings and Food Scraps category, are there other data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    a. C storage, decay rates, etc. for yard trimmings and food scraps
    b. Decay rates of food scraps, leaves, grass, and branches
    c. National yard waste compositions
    d. Precipitation range percentages for populations for the decay rate sensitivity analysis
6. For the Peatlands Remaining Peatlands category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider? Especially:
    a. We estimate a rapid decrease of peat production from 2010-2012, with a flattening out of the decrease after 2012. Is this in line with industry trends?
7. For the Peatlands Remaining Peatlands category, are there other data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    a. Peat production (mainly Alaska, which has not had reported peat production since 2012 due to a lack of survey responses from industry)
    b. Data to help us develop U.S.-specific emission factors—we currently use IPCC default emission factors.

Waste

General

1. Please provide your overall impressions of the clarity and transparency of the Waste chapter.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Waste chapter.

Wastewater

1. The wastewater source category relies on national production data from a variety of sources for calculating emissions estimates. Are there other data sources that EPA should be aware of and consider in the emissions calculations of this source?
2. Please provide input on any additional sources of wastewater outflow or BOD production that we may not consider in our industrial methane emissions calculations. Do our estimates of the percent of wastewater treated anaerobically seem reasonable?
3. For domestic wastewater emissions, please provide input on:
    a. Any additional sources for the N content of sludge, amount of sludge produced, and sludge disposal practices.
    b. The estimates of the percent of BOD removed by aerobic, anaerobic, and other treatment systems for our methane estimates.

   c. The protein estimates and overall calculations for nitrous oxide. For example, do you have suggestions for developing a country-specific factor, rather than the IPCC default factor, to estimate the amount of nitrogen from industrial and commercial sources co-treated with domestic wastewater?
4. Are there additional industries that are sources of methane or nitrous oxide emissions that should be included in the wastewater inventory? Are there available sources of national-level data for these industries?
5. Do you have suggestions for improving the discussion of our methodology? Is there any additional information that should be included to provide additional transparency?
6. Is the state of domestic and industrial wastewater treatment current and accurately described?

Landfills

Scale-Up Factor for MSW Landfills

A scale-up factor is applied in the inventory to account for landfills that do not report to the GHGRP Subpart HH (MSW landfills). We calculated a scale-up factor of 12.5% percent for the 1990-2015 Inventory based on the percent difference between the 1990-2014 Inventory emissions and the GHGRP emissions as reported for 2010-2015 and back-casted GHGRP emissions for 2005 to 2009. The GHGRP emissions from 2010-2015 were used to back-cast emissions for 2005 to 2009 using a linear Excel forecasting function. In the 1990-2015 Inventory, we applied the 12.5% scale-up factor to the back-casted emissions for 2005 to 2009, and the directly reported GHGRP emissions for 2010 to 2015. We applied the same 12.5% scale-up factor for the draft 1990-2016 Inventory for 2005 to 2016, and are working to refine the scale-up factor for the final 1990-2016 Inventory.

The steps we have taken to date to calculate a more precise scale-up factor include developing a list of facilities that do not report to the GHGRP by extracting GHGRP MSW landfills from the LMOP 2017 database and the Waste Business Journal (WBJ) 2016 database. This list currently includes more than 1,600 landfills. However, we are not confident that this list does not include C&D landfills or industrial waste landfills due to the lack of details in the LMOP or WBJ databases. Without expert insights, we believe a desk-top search would be required to identify any C&D landfills or industrial waste landfills that should be removed from this list.

Additionally, we are working on several manual QA/QC steps, with help from stakeholders, to confirm that no landfills in the list of non-reporting facilities can be matched to any GHGRP landfills. Matching the GHGRP facilities to those in the WBJ and LMOP databases is challenging due to the variety of names for a given landfill and the differences in GPS coordinates across the databases.

We are currently considering two options for a scale-up factor that are based on either:

   a) The percentage difference in total waste-in-place between the non-reporting facilities and the GHGRP MSW landfill facilities, or
   b) The percentage difference in net methane emissions between the non-reporting facilities and the GHGRP MSW landfill facilities.

While we have not completed a full QA/QC review of the list of non-reporting landfills, we are presenting two values for options (a) and (b).

a) Option (a) yields a scale-up factor of approximately 11%. See Table 1, orange cell. This value was determined from the estimated total waste-in-place for non-reporting facilities compared to facilities reporting to the GHGRP. Available waste acceptance data from LMOP and WBJ was used to determine waste-in-place for the non-reporting facilities. To calculate GHG emissions for non-reporting facilities, 11% of the total GHGRP emissions for each year of the time series would be applied. Note that this value is based on a pre-QA/QC review of the non-reporting landfills database. A QA/QC review is currently underway.

Table 1. *Scale-up Factor based on total waste-in-place (WIP) for 2015*

Calcs.2 (non-adjusted)	**WIP (MT)**	**%**	**Comments**
Non-reporting facilities (2015)	1,604,238,495	11	Does not exclude any C&D or inerts to be consistent with GHGRP total WIP.
GHGRP (RY2015)	12,936,398,280	89	Total WIP for reporting landfills (RY2015)
Total	14,540,636,775	100	

b) Option (b) yields a scale-up factor of approximately 26%. See Table 2, orange cell. This value was determined from estimated methane emissions for the non-reporting landfills. We used the Inventory Waste Model (first order decay methodology) and estimated annual waste disposal data that excludes an average amount of C&D and inert waste (23% of C&D and inert waste excluded per facility; same disposal amount included in the model for each year of operation) and the same default factors as applied in previous Inventories for DOC, MCF, etc. and a 10 percent oxidation factor. To calculate GHG emissions for non-reporting facilities, 26% of the total GHGRP emissions for each year of the time series would be applied. Note that this value is based on a pre-QA/QC review of the non-reporting landfills database. A QA/QC review is currently underway.

Table 2. *Scale-up Factor based on Net Emissions, as calculated with adjusted WIP for 2015*

Calcs.3 (adjusted for C&D/inerts)	**Net Emissions (MMT)**	**%**	**Comments**
1990-2015 Inventory	4.63	—	Total as calculated by the Waste Model using the back-casted GHGRP data and 12.5% scale-up factor for 2005-2016. Included for reference.
Non-reporting facilities (2015)	1.27	26	Excludes the GHGRP average of C&D/inert waste of 23% for each non-reporting facility.
GHGRP (RY2015)	3.64	74	Total as reported to the GHGRP in RY2015. Data obtained from FLIGHT in CO_2e.
Total	4.91	100	

Scale-Up Factor Questions:

1) Please comment on additional datasets that we can use to generate and/or refine a list of non-reporting landfills. Datasets with WIP data and start/closure years are needed to develop a scale-up factor for landfills that do not report to the GHGRP.

2) How should we consider landfills that "off-ramp" from the GHGRP going forward with respect to the scale-up factor? For context, only facilities that generate 25,000 MT CO_2e annually are required to report to the GHGRP. A facility can off-ramp (i.e., stop reporting) to the GHGRP if it meets one of the following criteria:
   a. Emissions < 15,000 MT CO_2e for 3 consecutive years
   b. Emissions < 25,000 MT CO_2e for 5 consecutive years
   c. Approximately 16 landfills have off-ramped to date. If we consider these landfills as part of the non-reporting set of landfills, should we adjust the scale-up factor accordingly for the year(s) after facilities stop reporting?
3) Please comment on the best approach for applying a scale-up factor. We are currently applying the same scale-up factor for 2005 to 2016. Does it make more sense to apply a scale-up factor for blocks of time (e.g., 5 years), annually, when GHGRP facilities off-ramp, etc.?

Landfill Methane Oxidation for 1990-2004 in the Inventory Time Series (for MSW Landfills)
For the period of 1990-2004 in the Inventory time series, a national estimate of methane generation and emissions are calculated using a combination of secondary data sources that detail the annual quantity of waste landfilled and the annual quantity of methane recovered from facilities with landfill gas collection and control systems. A 10% oxidation factor is applied to all facilities for the years 1990 to 2004.

We are considering revisions to the value of the oxidation factor and possibly using two oxidation factors, one for waste disposed at facilities with landfill gas collection and control systems, and the other without. We currently do not have a way of assigning a percentage of waste disposed in landfills with gas collection or without for those years. Given that this is a national inventory and we do not have facility-specific data for all landfills in the U.S., we need data sources that discuss trends in the installation of landfill gas collection systems, including when the system became operational and at which facilities. The data available for 1990-2004 is currently national level waste generation; it is not landfill-specific.

Oxidation Questions:

1) Please comment on available data sources to address trends in the installation of landfill gas collection systems.
2) Please comment on appropriate oxidation factors for these two general categories (with and without landfill gas collection systems).
3) Please comment on an appropriate oxidation factor if we were to use one oxidation factor for all waste disposed at landfills between 1990 and 2004.
4) Please comment on methane leakage (e.g., from cracks and fissures in the cover) with respect to oxidation factors. If we apply a higher oxidation factor, say 20%, should we also apply a leakage factor to waste disposed at landfills with gas collection and control, or all landfills in general?

Disposal Factor for Industrial Waste Landfills
Industrial waste is estimated for two sectors, pulp & paper and food & beverage. We apply a default disposal factor to estimated annual production data for both sectors.

For pulp & paper, we assume a disposal factor of 5% of the annual amount of woodpulp and paper and paperboard produced per year. The same 5% disposal factor is applied annually across the time series (1990-2016) for pulp & paper.

For food & beverage, we apply a factor that considers the amount of waste landfilled from an EPA study in 1985 (EPA 1993, as referenced in the Waste chapter) and the annual amount produced in a given year in the time series. The production data is based on the following: red meat carcass weight, poultry carcass weight, vegetables processed (apples, citrus fruit, other non-citrus fruit, and grapes). The disposal factor varies by year because it incorporates the annual production for that year.

Disposal Factor Questions:

1) Please comment on the pulp & paper disposal factor and whether we should use a disposal factor based on the GHGRP Subpart TT data.
2) Please comment on new studies that include data on food processing to landfill disposal ratios or annual quantities landfilled.

United States
Environmental Protection
Agency

Summary of Public Review Comments and Responses:
Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017*

April 2019
U.S. Environmental Protection Agency
Office of Atmospheric Programs
Washington, D.C.

Responses to Comments Received during the Public Review Period on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017*

Preface

EPA thanks all commenters for their interest and feedback on the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Per Federal Register Notice 2019-01545 published on February 12, 2019, EPA announced document availability and request for comments on the draft "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017" report. The EPA requested recommendations for improving the overall quality of the inventory report finalized April 11, 2019 and submitted to the United Nations Framework Convention on Climate Change (UNFCCC), as well as subsequent inventory reports.

During the 30-day public comment period which ended March 14, 2019, EPA received 13 sets of comments, including 33 unique comments in response to the notice. This document provides EPA's responses to technical comments on methods and data used in developing the annual greenhouse gas inventory. The verbatim text of each comment extracted from the original comment letters is included in this document, arranged by commenter. Full comments can be found in the public docket here: https://www.regulations.gov/docket?D=EPA-HQ-OAR-2018-0853. Note, at time of publication of this document some comments sent to EPA via email were still pending posting to Docket but should be available shortly. Where available, Docket ID numbers are noted under commenter's name for ease of reference. EPA's responses to comments are provided immediately following each comment excerpt.

Commenter: GPA Midstream Association

Matt Hite

Docket ID Number: EPA-HQ-OAR-2018-0853-0007

Comment 1: GPA Midstream urges EPA to reconsider the methodology EPA uses to calculate Greenhouse Gas Emissions (GHGs) for the midstream Gathering and Boosting (G&B) segment of the natural gas production and distribution sector. As is stated in Chapter 3 of the Inventory, EPA does not use data from the Greenhouse Gas Reporting Program (GHGRP) to calculate the emissions for this segment. Instead, EPA uses emissions factors from the 1996 EPA/GRI report and Zimmerle et al. (2015) study. GPA Midstream has significant concerns about the use of both data sources for emissions factors associated with the G&B segment, but we will address our comments to the limitations of the 1996 EPA/GRI data.

As EPA has recently acknowledged, the 1996 EPA/GRI report is now over two decades old and was focused on the equipment and facilities used to produce natural gas. In the recent Proposed Rule, Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources Reconsideration 83 Fed. Reg. 52056 (October 15, 2018) – Docket ID No. EPA-HQ-OAR-2017-0483 (NPSP OOOOa), EPA acknowledged in the Background Technical Support Document that the 1996 EPA/GRI report "does not have specific information on major production and processing equipment counts for the gathering and boosting segment." TSD § 2.3.4 at 15-16. In short, the data from the 23-year old GRI study is not only outdated, but not from the G&B industry segment, and therefore the data should not under any circumstances be used to evaluate emissions from the G&B industry.

During a comment period for NSPS OOOOa, GPA Midstream highlighted EPA's clear error in relying on the 1996 EPA/GRI study to estimate emissions from the model midstream G&B plant. In order to counter the outdated, inapposite data from the EPA/GRI 1996 report, GPA Midstream gathered an inventory from member companies of equipment found at current-era G&B facilities. [1] This new data was, in part, gathered from the publicly available data found in the GHGRP, 40 CFR Part 98 Subpart W (Subpart W) for the G&B segment. However, because Subpart W (at 40 CFR Part 98.236(a)(9)) directs operators to report equipment types (separators, meters/piping, gathering compressors, in-line heaters and dehydrators) across a basin, GPA Midstream could not gather a per-site count directly from the reported data.[2] Accordingly, GPA Midstream solicited member companies to submit facility-level data. Table 1 below compares EPA's model plant (based on the 1996 data from non-G&B facilities) with GPA Midstream's updated model plant (based on current G&B facility data). EPA asserts that each facility has 11 separators, seven meters/piping, five gathering compressors, seven in-line heaters and five dehydrators. GPA Midstream's actual data demonstrates that EPA's numbers are not representative of current G&B facilities.

Table 1- Updated Gathering and Boosting Model Plant

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[1] GPA Midstream's comments and the supporting data are available on the NSPS OOOOa docket and are incorporated here by reference. https://www.regulations.gov/document?D=EPA-HQ-OAR-2017-0483-1261

[2] GPA Midstream has long advocated for Subpart W reporting for the GHG Reporting Rule to be on a per-facility basis. Had the regulation required equipment to be reported at an individual facility level and not a basin level, the data would have been even more precise in informing this rulemaking.

Equipment	Model Plant (GRI)	GPA Model Plant
Separators	11	5
Meter/Piping	7	6
Gathering Compressors	5	3
In-Line Heaters	7	1
Dehydrators	5	1

GPA Midstream compiled its model plant from eight companies and includes 1,821 G&B sites. Due to the basin-wide reporting required by Subpart W, the data may overstate the actual number of meters at a typical G&B facility. Specifically, basin level reporting in Subpart W requires companies to report equipment outside of a traditional G&B facility boundary, such as meters located at production well sites where producers deliver gas to midstream operators. Hence, the rolled-up basin data in Subpart W for G&B facilities included meters located at production well pads. Depending on the size of the basin and the way in which companies document their inventory, GPA Midstream could not readily identify and separate out certain reported meters that are not within the G&B facility but are included in the basin data set. When this was the case, to be conservative in its approach, GPA Midstream used EPA's assumption of 7 meters/site. However, GPA Midstream believes this to be a conservatively high number.

If EPA continues to use a similar flawed methodology to count equipment when EPA prepares the Inventory as EPA used in its NSPS OOOOa support documents, the resulting emissions estimates will be biased high – potentially more than double what they should be, since there is a direct correlation between the size of a G&B facility (measured by the scope of equipment) and the total emissions per site of methane, VOCs, and Hazardous Air Pollutants (HAPs). Accordingly, to more accurately estimate midstream emissions, we urge EPA to utilize GPA Midstream's model plant equipment numbers which can be entered directly back into the calculation analysis and scaled up. At a minimum, EPA should utilize the data gathered from the reporting EPA has required industry to provide under Subpart W to inform the Inventory. If the data gathered in Subpart W is not useful, EPA should revise the reporting rule.

Conclusion

In short, GPA Midstream asks EPA to revise the methodology EPA uses to calculate GHGs for the midstream G&B segment of the natural gas production and distribution sector to reflect the current, more reliable data GPA Midstream has collected from the G&B segment and EPA's subpart W database. GPA Midstream stands ready to answer any questions the Agency may have and looks forward to working with EPA to ensure the GHG data in the Inventory is a reliable estimate of GHG emissions from midstream sector.

Response: The GHGI does not rely on data from GRI/EPA 1996 or Zimmerle et al. 2015 to estimate methane from the gathering and boosting segment. The GHGI emissions estimates are instead developed using the following data sources:

- ***Marchese et al. 2015 and an estimate of station counts (not an estimate of component counts as implied by the comment) for gathering and boosting stations, including episodic events***
- ***GHGRP data for gathering pipeline leaks and blowdowns***

For gathering and boosting stations, EPA proposed to update estimates to use the reported GHGRP data in this year's GHGI, but stakeholder feedback received throughout the development of this year's

GHGI supported delaying such an update until review of upcoming study data and additional years of GHGRP data.

For gathering pipeline leaks and blowdowns, this source was previously estimated using GRI/EPA 1996 data, but has been updated in this year's GHGI to use annual GHGRP data.

Commenter: American Gas Association

Pamela Lacey

EPA Docket ID Number: EPA-HQ-OAR-2018-0853-0008

Comment 2: **Update to Emission Factor for Estimating Emissions from Transmission Pipeline Blowdowns**

In a November 27, 2018 letter to EPA, AGA commented on updates[3] EPA was considering for estimating transmission pipeline blowdowns in the 2019 EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI). At that time, EPA was considering updating the emission factor for transmission pipeline blowdowns based on data submitted for the 2016 reporting year under Subpart W of the GHG Reporting Program (GHGRP). In the AGA letter and a subsequent phone call, AGA identified issues with the EPA proposed emission factor for pipeline blowdowns because it included flawed data reported for 2016 by one company. The initial 2016 data from that company included an error, which was subsequently corrected by the reporting company. Thus, the current Subpart W dataset available to EPA corrects the erroneous data. AGA's letter also noted that 2017 reporting year data were also available and should be considered when developing a new emission factor. Ultimately, AGA recommended waiting an additional year to update the pipeline blowdown emission factor, because the emission factor using 2017 blowdown data was lower than the emission factor using 2016 data. A third year of data could potentially provide insight into whether one year was more representative than the other. For example, 2016 data may be atypical due to program maturity associated with the first year of reporting and/or a higher occurrence of blowdowns from construction / commissioning in 2016 that may not be representative of typical conditions.

In addition, it should be noted that companies are making concerted efforts to reduce blowdowns and blowdown emissions. This may lead to a downward trend over time.

In a February 12, 2019 Federal Register notice (84 Fed. Reg. 3444), EPA requested comment on the 2019 draft GHGI report, which updates the emission factor for transmission pipeline blowdowns using the average from corrected 2016 data and 2017 data. The notice also requests feedback on whether year-specific emission factors should be applied for 2016 and 2017, and whether the current emission factors should be applied for earlier years of the time series.

AGA appreciates EPA understanding the issue associated with the flawed 2016 data and revising the emission factor that was initially proposed. While AGA recommended waiting an additional year to integrate Subpart W data, we understand EPA's desire to proceed with the updated emission factor and applaud efforts to utilize Subpart W results to improve emission estimates for natural gas operations.

In response to EPA's request for feedback and because there are differences in 2016 and 2017 data, AGA recommends using event-specific emissions for 2016 and 2017, and applying the historical/previous

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[3] "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017: Other Updates Under Consideration," U.S. EPA (November 2018).

emission factor for the earlier years in the time series. The resulting time series would show a one year increase in emissions in 2016 and similar emissions for other years. Alternatively, EPA could refrain from updating the emission factor in the 2019 inventory report, gather an additional year of Subpart W data, and update the transmission pipeline blowdown emission factor and emission estimates in the 2020 annual inventory report. The third year of Subpart W data (for 2018) could add insight regarding year-to-year variability and whether any data appears to be anomalous.

AGA remains concerned that the first reporting year (2016) may be lower quality data or an atypical year (e.g., more construction projects than representative of an average year), and requests that EPA continue to conduct an annual review of the pipeline blowdown emission factor that integrates additional Subpart W data for the most recent reporting year. For example, EPA should add the 2018 reporting year data when considering the appropriate transmission pipeline blowdown emission factor for the 2020 GHGI. The dataset that includes three years of Subpart W data should be carefully reviewed to consider not only average emissions from the cumulative dataset, but also year to year emissions and emissions and counts by event type for each year. The objective should be developing an emission factor that reflects representative or typical conditions for transmission pipeline operations. AGA offers its assistance in reviewing the data to help develop a high-quality emission factor.

Response: We agree with the comment and have updated the final GHGI to use year-specific GHGRP data for 2016 and 2017 emissions and GRI/EPA 1996 data for 1990-2015 emissions. We plan to review 2018 (and future years) GHGRP data to update the time series, assessing year-specific factors or other options such as average factors.

Commenter: American Petroleum Institute

Karin Ritter

Comment 3: The comments below consist of brief observations and recommendations on several segments of the draft Petroleum and Natural Gas Systems sections of the 2019 GHGI.

The letter also includes an attachment with preliminary comments on potential future revisions to the methodology of estimating emissions from offshore platforms.

1. Gathering & Boosting (G&B) stations emissions

In its October 2018 memo, EPA presented three scenarios for using GHGRP data to estimate G&B station emissions. EPA ultimately decided not to update its estimation methodology for G&B stations due to stakeholder feedback that supported maintaining the current GHGI methodology until new data becomes available.

EPA is seeking feedback on potentially applying a GHGRP-based methodology to estimate CO_2 emissions from G&B stations for inclusion in the final 2019 Inventory, while maintaining the current Inventory approach for CH_4.

API Comments:

In its August 22, 2018 comment letter to EPA API supported EPA's proposed basin level scaling approach for G&B stations emissions. At the same time API recognized the lack of national data for the G&B segment, which would require further research and analysis prior to adopting an amended methodology.

Furthermore, API's December 10, 2018 letter to EPA conveyed its general support for using GHGRP data that is based on actual equipment counts, measurements, or engineering principles. As was pointed out in that letter, calendar year 2017 is only the second reporting year for G&B sources, and emissions estimates for some of these sources is lacking since they are based on generic emission factors.

API continues to request that EPA wait to have an additional year of GHGRP reported data, and new information that may be forthcoming from on-going studies, prior to amending its emission estimation methodology. Such an approach would ensure consistency for G&B stations emissions estimation methodology for both CO_2 and CH_4. Therefore, API is urging EPA to refrain from using a basin scaling based approach for estimating CO_2 emissions while relying on nationwide total dry gas delivery to market for CH_4, emission estimation.

Response: We agree with the comment and plan to review relevant upcoming study data and additional years of GHGRP data and will consider an update for this estimate for future GHGIs.

Comment 4: **2. HF Oil well completions and workovers -** *EPA revised the HF oil well workovers methodology to use the same general approach as for HF oil well completions. EPA states that stakeholder feedback supported an approach of using GHGRP data to update activity and emissions factors on an annual basis from 2016 forward.*

API Comments:

API acknowledges EPA's revised methodology which follows API's request (August 2018 memo) for establishing separate emission factors for oil well completions and oil well workovers. This is now enabling consistent reporting of emissions from these respective activities in the Exploration and Production segments of the inventory.

Response: Noted.

Comment 5: **3. Refinery emissions -** *EPA indicates that there are minimal changes in recalculated* CH_4 *and* CO_2 *emissions for 1990 to 2015 for this segment, with some changes for 2016 recalculations, in accordance with GHGRP submission revisions.*

EPA additionally states that one stakeholder noted a recent study that measured three refineries and found higher average emission than those presented in the Inventory. That stakeholder suggested that EPA evaluate the study and any additional information available on this source.

API Comments:

As initially recommended and supported by API, emissions from the petroleum refining sector are based on year-specific emissions data, which is obtained directly from EPA's GHGRP for all the years since the initiation of reporting in 2010. EPA's GHGRP estimation methodology is very detailed and it is based on site specific information and measurement data. Consequently, the GHGRP approach results in very robust estimates of GHG emissions from U.S. refineries.

Although API recognizes the need to review and evaluate new relevant data, API cautions against jumping to unwarranted conclusions based on measurements from a single study that presents measurements obtained during flyover transects of three refineries only. It is imperative to recognize that aircraft-based mass balance measurement techniques are difficult to conduct as they are highly dependent on weather conditions and may be impacted by adjacent sources. Moreover, the results obtained are based on sampling during short-term time flight windows that are not representative of yearly average emissions from refining operations at the facility.

Response: We agree with the comment and have not updated the methodology or data source for refineries in the GHGI. We will continue to review new relevant studies as they become available.

Comment 6: **4. Off-shore platforms**

Among its planned improvements EPA noted that it is considering updates to the offshore platform emissions calculation methodology, per the discussed in the April 2018 memo titled, "Additional Revisions Considered for 2018 and Future GHGIs". EPA states that the current emission factors were based on data from the 2011 Bureau of Ocean Energy Management's (BOEM) dataset, while the 2014 BOEM data are already available. Also, being considered is a different source for platform counts.

API Comments:

API supports utilizing the 2014 BOEM data to update the emission estimation methodology for offshore platforms in order to ensure the utilization of the most current representation of activities and emissions. As the methodology is being updated it ought to be noted that GHG emissions from deep-water GoM facilities have better emissions controls than most international oil and gas production operations. Since GHG emissions are a global concern it is advisable that the U.S. national inventory should strive to highlight the difference between emissions from GoM production as compared to oil and gas production in other offshore areas.

In the attachment to this letter API provides an initial set of specific comments regarding potential improvements to the offshore platforms' methodology in response to EPA's preliminary methodology improvements presented in its April 2018 memo.

API plans to continue to compile and analyze greenhouse gas (GHG) emissions data for petroleum and natural gas systems and is committed to working with EPA in the future on utilizing data provided through EPA's mandatory GHG reporting program (GHGRP) and other relevant information sources.

API welcomes EPA's willingness to work with industry to improve the data used for the national inventory. API encourages EPA to continue these collaborative discussions and is available to work with EPA to make best use of the information available under the GHGRP, or other appropriate sources of information/data, to improve the national emission inventory.

Response: We plan to consider updates to this source for the 2020 GHGI to allow the GHGI to reflect the best country-specific information available.

Comment 7: API is providing below some initial specific comments on the approach presented by EPA on revising the estimates of GHG emissions from Offshore Platforms.[4]

p. 19, Table 18 - EPA should reconsider the practice of categorizing emissions by the water depth of the facility. EPA's approach gives the erroneous impression that shelf production is environmentally preferable (from an air emissions standpoint). That is clearly not the case. Fewer, more dispersed deep-water facilities with fewer wells produce much more oil and gas. The 59 deep-water surface structures

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[4] U.S. EPA, "Additional Revisions Considered for 2018 and Future GHGIs", April 2018 Memo.

(about 3% of the GoM total) produce approximately 90% of the oil and 60% of the natural gas. Emissions per barrel of oil equivalent (BOE) are thus much lower for deep-water facilities.

Response: We plan to consider updates to this source for the 2020 GHGI and will consider different categorizations of platforms/complexes.

Comment 8: p. 19 excerpt: *As seen in Table 17, when gas platforms are defined as those producing more than 100 thousand cubic feet of gas per barrel of hydrocarbon liquid (mcf/bbl), there are no deep-water gas platforms in the GOADS database, resulting in no EF for this platform group. EPA assigned the deep-water oil platform EF to deep-water gas platforms as a surrogate.*

This may be a moot point given the absence of deep-water platforms and the likelihood that deep-water production will continue to be predominantly oil. However, dry gas platforms tend to be less complex with fewer wells and less processing equipment. Assigning the oil platform EF to such gas platforms would significantly overstate emissions.

Response: We plan to consider updates to this source for the 2020 GHGI and will consider different options for emission factors for deep-water gas production, if relevant.

Comment 9: p. 20 excerpt: *The activity data for the calculation of these emissions from 1990 through 2008 was provided by U.S. Mineral and Mining Service (MMS)*

API assumes that EPA intended to note that MMS was the Minerals Management Service.

Response: We agree with the comment and will correct the name of the MMS in future memos.

Comment 10: p. 21, Table 19: While the discussion is about flaring and venting, this table only includes the flaring numbers. An important development over the past 10 years is the reduction in gas being vented. Even though oil-well gas production (for which there is a greater incentive to flare) now (since 2016) exceeds gas-well gas production, the volume of gas flared or vented has declined (see chart below). While total gas production has also declined, total flaring/venting volumes have remained relatively stable at around 1% of total gas production.

Response: We plan to consider updates to this source for the 2020 GHGI and will consider different options for reflecting trends in venting and flaring.

Comment 11: Platform emissions are a function of complexity, power requirements, processing equipment, maintenance, reliability, and control systems. Although deep-water platforms tend to be more complex, that is not always the case and emissions are not a direct function of water depth. A different classification scheme that considers complexity and processing capacity should be considered. One option would be to establish emission factors by facility category (e.g. FPSOs, TLPs, production semis, major fixed platforms, minor satellite platforms, guyed towers, and spars).

Response: We plan to consider updates to this source for the 2020 GHGI and will consider different categorizations of platforms/complexes.

Comment 12: The data source for vented and flared volumes is EIA's compilations of natural gas gross gas withdrawal for the time series 1997-2017.[5]

Response: The data source used in the memo table was BOEM's Oil and Gas Operations Reports (OGOR). OGOR-B provides lease disposition data, including codes for flared gas (Disp codes 21 and 22) and vented gas (Disp codes 61 and 62).[6] We plan to consider updates to this source for the 2020 GHGI and will consider different data sources for flaring emissions, such as EIA's compilation.

Comment 13: While EIA data (the only flaring data available online) do not distinguish between flaring and venting volumes, the trend favors flaring (vs. venting) because most gas is now produced at modern deep-water facilities. A 2017 BSEE report (Argonne National Laboratory, 2017, Tables 1 and 2)[7] confirms that oil-well gas is primarily flared (in those instances when not captured and exported to market) and that nearly all the gas released from floating deep- water structures is flared. Given the much higher GHG effect of methane (vs. CO_2), this is a very important distinction and highly favorable trend.

Response: We plan to consider updates to this source for the 2020 GHGI and will consider different data sources for flaring emissions, such as OGOR-B and EIA's compilation, and different methods for estimating the split between venting and flaring emissions.

Commenter: Private Citizen (Chadwick)

Bridget Chadwick

Comment 14: **Re: Table A-44 Electric Power Generation by Fuel Type [Percent]**

The total amount of electricity generated for the "electric power sector" provided in the bottom row of Table A-44 is less than what the Energy Information Administration's (EIA) reports in their October 2018 Monthly Energy Review (MER) Table 7.1 Electricity Overview, column #1 for the "electric power sector" (which is defined elsewhere in the MER as power plants "within the NAICS 22 category whose primary business is to sell electricity, or electricity and heat, to the public").

From my calculations, it seems that the EPA's total does not include the electricity generated from "other gases" (defined as "blast furnace gas, and other manufactured and waste gases derived from fossil fuels" in footnote d of Table 7.2b Electricity Net Generation: Electric Power Sector); hydroelectric pumped storage; biomass wood; biomass waste; and the electricity generated from "batteries, chemicals, hydrogen…non-renewable waste (municipal solid waste from non-biogenic sources and tire-derived fuels)" (footnote i of Table 7.2b). The amount of electricity generated from these sources are provided in columns #4, 6, 8, 9 and 13 of Table 7.2b. (The amount of electricity generated from batteries, chemicals etc. is the "Total" electricity generated provided in column #13 minus the total of electricity generated by all other sources in columns #1-12).

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[5] Natural Gas Gross Withdrawals and Production, Federal offshore GoM, vented and flared; https://www.eia.gov/dnav/ng/NG_PROD_SUM_DC_R3FM_MMCF_A.htm

[6] https://www.data.boem.gov/Main/OGOR-B.aspx

[7] BSEE, Venting and Flaring Research Study Report, January 2017; https://www.bsee.gov/sites/bsee.gov/files/5007aa.pdf

The electricity generated from biomass wood and waste, as well as hydro-electric pumped storage should be included in the "renewables" energy source category. Electricity generated from fossil fuel waste, "other gases" and "batteries…municipal solid waste" should be aggregated either with the petroleum category or provided in a separate row. In 2017 then, the breakdown of the electric power sector would be as follows: coal 31.1%; natural gas 30.5%; fossil fuel waste 0.3%; petroleum 0.5%; nuclear 20.9% and renewables 16.8%.

Response: Table A-44 is based on EIA's MER, Table 7.2b Electricity Net Generation: Electric Power Sector. As noted in the comment above, in the Public Review report this table excludes electricity generation from "Other Gases," "Hydro-electric Pumped Storage," "Biomass (Wood and Waste)," and "Batteries…non-renewable waste".

We agree that electricity from "Biomass (Wood and Waste)" should be included under the Renewables category and that change was made in the Final Report. We also agree that electricity from "Other Gases," should be included and that change was made in the Final Report as a new "Other" category in the table with a footnote to clarify what this is referring to.

"Hydro-electric Pumped Storage" is not considered a "fuel" and therefore was not including because the table is specifically referring to fuels used to generate electricity.

Other sources of electricity (i.e., batteries, chemicals, hydrogen, pitch, sulfur, miscellaneous technologies, purchased steam, and non-renewable waste [municipal solid waste from non-biogenic sources, and tire-derived fuels]) are also excluded from the table for the following reasons:

- ***Several of these items (i.e., batteries, chemicals, hydrogen, pitch, sulfur, and miscellaneous technologies) are not considered "fuels" and are therefore not included.***
- ***For purchased steam, there is not any straightforward way of determining whether the fuel that generated the steam was coal, oil, gas, etc. The actual "fuel" that was used to generate the steam cannot be determined.***
- ***Non-renewable wastes (e.g., non-biogenic MSW, tire-derived fuels) could be included, but currently there is not sufficient data to separate this from the other elements described above.***

Further research will be conducted to potentially include other categories in the table in future Inventory reports, to the extent that data are available. A note was added in the Final Report version of the text after the table further explaining how the table was developed and what was included.

Comment 15: **Re: Table A-43 Electricity Consumption by End-Use Sector [billion kilowatt-hours] and Table 2-5 CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector [MMT CO_2 Eq.]**

The EPA's method of allocating emissions from the electric power sector to each end-use sector "according to its share of aggregate electricity use" is in agreement with the EIA's method where emissions are allocated "in proportion to each sector's share of total electricity retail sales".

However, the EPA's electricity consumption for the industrial sector in Table A-43 should not include the "direct use" of electricity (non retail) by the industrial sector MER's Table 7.6 Electricity End Use, column #6 with the retail electricity sold to the industrial sector, Table 7.6 column #3.

Total CO_2 emissions from electricity consumption by all the end-use sectors provided in EPA's Table 2-5 agrees with what the EIA reports in MER Table 12.6 Carbon Dioxide Emissions from Energy Consumption: Electric Power Sector (minus the CO_2 emissions that the EIA reports for non-biomass waste). If the "direct use" of electricity by the industrial sector is handled separately, see below, then the emissions from retail electricity consumption by each end-use sector, presented in the 2nd to last column of MER Tables 12.2, 12.3, 12.4 and 12.5 for the residential, commercial, industrial and transportation sectors, respectively, should correspond with the electricity emissions in EPA's Table 2-5.

The CO_2 emissions from "direct use" of electricity by the industrial and commercial sectors should be inventoried separately from electric power sector emissions. The EIA provides total CO_2 from the electric power sector and "direct use" in their US Electricity Profile spreadsheet, sheet #7 Emissions. With data provided in the MER Table 12.6, the CO_2 emissions from "direct use" can be calculated.

Response: "Direct Use" of electricity in EIA's MER Table 7.6 refers to electricity generated by industrial and commercial sector plants (both combined heat and power and non-combined heat and power) that is consumed onsite for processes such as manufacturing, district heating/cooling, and uses other than power plant station use. Electric power sector emissions do not include "direct use" (they are included in the industrial and commercial sector emissions). Therefore, "Direct Use" should not necessarily be used to distribute electric power emissions. In addition, emissions from "station use" should be not necessarily be distributed to end-use sectors because those are exclusively electric power emissions. Further research can be conducted to obtain further levels of data granularity and potentially separate electric power distributed electricity emissions from electric power "station use" emissions. Some updates and clarifications were made to Table A-43 as part of the Final Report.

Comment 16: **Re: Table 2-13 Transportation-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)**

Using Federal Transit Administration data, the EPA should disaggregate emissions for passenger rail from freight rail. The disaggregation would allow analysis of the passenger transportation sector, separate from freight transportation.

Response: GHG emissions from the rail sector are broken out by freight rail and passenger rail in Annex 3, Section 3.2 (Tables A-123 and A-124).

Commenter: Private Citizen (Laitner)

John A. "Skip" Laitner

Comment 17: First, a positive comment on the current EPA effort. Second, emphasizing the need to provide a stronger forward-looking context in which the final inventory is to be produced. And finally, the need to bring forward and highlight a more proactive emphasis on the role of energy efficiency and resource productivity as key reasons why the growth of emissions over the period 1990 to 2017 – especially the growth of energy-related carbon dioxide emissions – has been somewhat stabilized (even as the robustness of the economy remains reasonably strong).

As to the first item? I want to extend my compliments on the EPA effort. I greatly admire the professional effort, the solid documentation of data and methodologies, and the clarity of the presentation. I congratulate the staff on a first- rate effort.

Response: EPA appreciates the commenter's support for the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017.

Comment 18: Second, the evidence documents a compelling need for much more than merely a historical context.

On page ES-1, lines 7-13, for example, the report cites Article 2 of the UNFCCC, noting that the ultimate objective of the Convention is to achieve ”stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time- frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

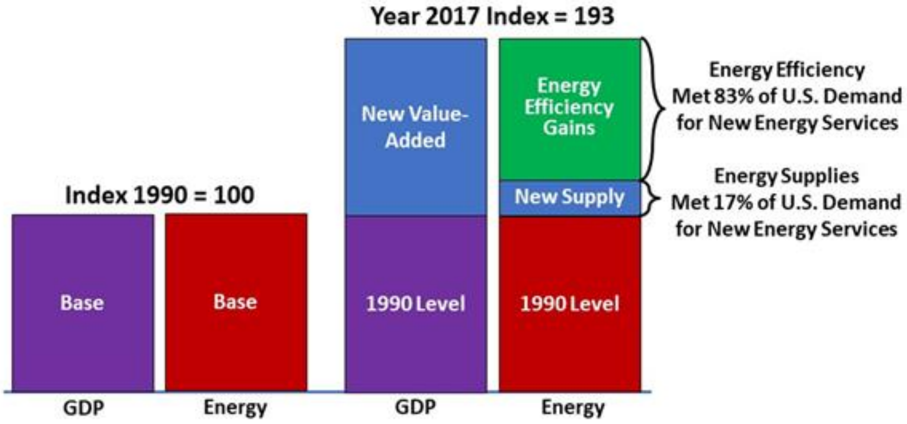
I’ve had the opportunity to talk directly with a number of the authors who participated in the writing of the IPCC Special Report on Global Warming of 1.5 ºC released mid-October last year. Climate scientists have made it very clear that we’ve already dangerously interfered with the natural climate processes, and that by 2030, the world will need to cut annual greenhouse gas emissions by about half. And perhaps 80 percent or more by 2050.

Given that urgency, it seems relatively straight forward for the EPA to acknowledge: (a) current levels of emissions are not at all consistent with Article 2 of the UNFCCC; and (b) that to ensure the prevention of dangerous anthropogenic interference with the climate system, perhaps even the healing of the climate system, the current magnitude of emissions should be cut roughly in half by 2030 through a portfolio of measures including much greater levels of energy efficiency, resource productivity, renewable energy technologies, and a much more productive infrastructure.

Finally, I think it important to inform policy and legislative leaders, businesses, and the average member of the public so that they understand it is the smarter use and the more productive deployment of aggregate resources that can help us reduce emissions by half by 2030. Even a cursory review of data will show that it is not simply a reduction in carbon intensity that has slowed the growth of emissions. Rather, there is a much bigger momentum of energy efficiency that has already driven positive outcomes. I highlight this in the chart I’ve put together below.

As you find it useful, I can more deeply explain the data and the logic that underpins the findings highlighted in the chart. Long-story short? Since 1990, greater energy efficiency has met about 83% of the new demands for energy services to power our economy (which nearly doubled over the 1990-2017 time horizon). New energy supplies, on the other hand, have met only 17% of those new energy service demands.

Since 1990 Energy Efficiency Met 83% of U.S. Demand for New Energy Services While New Energy Supply Only 17%



Source: John Laitner based on U.S. Energy Information Administration Data, March 2019.

With these comments, and for the benefit of building up the public record to highlight much greater opportunities to put energy and resource productivity to greater work, let me provide reference to two major assessments that might inform the EPA about the scale and emerging opportunities that can lower greenhouse gas emissions. The first is a 2018 international exercise while the second is a 2012 assessment done for the U.S. economy. Both examine the opportunities through the year 2050.

Grubler, A., C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. D. Stercke, J. Cullen, S. Frank, O. Fricko, F. Guo, P. Havlík, M. Gidden, D. Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp and H. Valin (2018). "A Low Energy Demand Scenario for Meeting the 1.5oC Target and Sustainable Development Goals without Negative Emission Technologies." Nature Energy [DOI: doi 10.1038/s41560-018-0172-6].

Laitner, JAS, S. Nadel, R. Elliott, H. Sachs, S. Khan (2012). The Long-Term Energy Efficiency Potential: What the Evidence Suggests. Washington, DC: American Council for an Energy-Efficient Economy. https://aceee.org/research-report/e121.

Response: EPA thanks the commenter for the additional information and perspective on the role of energy efficiency improvements in driving historical and possible future reductions of greenhouse gas emissions. The inventory is a policy-neutral, technical report providing information on current GHG emissions and sinks and trends prepared per reporting UNFCCC Annex 1 National GHG Reporting Guidelines (see Box ES-1) and as such, it is not well-suited as a document in which to outline mitigation opportunities and goals. The Inventory does include some discussion of trends and carbon intensity in Box 3-5: Carbon Intensity of U.S. Energy Consumption starting on Page 3-31 including Figure 3-16: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP on Page 3-33.

Commenter: Environmental Defense Fund and Clean Air Task Force

David Lyon, Ph.D., Lesley Fleischman, David McCabe, Ph.D.

Comment 19: In our comments, we discuss a recently published, peer-reviewed paper that estimates 2015 U.S. Petroleum and Natural Gas Systems emissions and suggest similar approaches that could be used by EPA to more accurately estimate emissions by incorporating facility-level and basin-level data into the GHGI.

Additionally, we support EPA's decision to continue to use empirical, site-level data from Marchese et al (2015) to estimate methane emissions from gathering and boosting stations. Emissions would have been greatly underestimated if EPA changed to the proposed approach based on EPA Greenhouse Gas Reporting Program (GHGRP) emissions data. For future considerations of updates to this source, we suggest that EPA consults our stakeholder feedback on the 2018 GHGI memos, in which we describe an alternative method that uses data from both GHGRP and Marchese et al to most accurately estimate total emissions with a best approximation of source-specific emissions.

1. The current GHGI underestimates Petroleum and Natural Gas Systems methane emissions

A recently published paper in Science, Alvarez et al (2018), synthesized data from several recent studies to estimate 2015 U.S. oil and gas (O&G) supply chain methane (CH_4) emissions of 13±2 teragrams (Tg) CH_4, approximately 60% higher than the estimate for Petroleum and Natural Gas Systems for 2015 in the 2017 EPA GHGI. The O&G production segment is the largest source of this difference (7.6 vs 3.5 Tg) with three other segments also having higher emission estimates than the GHGI: gathering (2.6 vs 2.3 Tg), processing (0.72 vs 0.44 Tg), and transmission and storage (1.8 vs 1.4 Tg).

Alvarez et al (2018) used facility-level measurements as the primary data source for estimating emissions, including data from over 400 well pads in six basins collected with ground-based, mobile approaches such as EPA Other Test Method 33A (OTM 33A). Site-based emission estimates were validated with top-down, basin-level data derived from aerial mass balance estimates in nine basins. The paper also developed an alternative emission inventory using a component-level approach analogous to the GHGI for the production segment with updates to specific source categories. For example, pneumatic controller emissions were estimated with a combination of GHGRP activity data and custom emission factors (EFs) based on Allen et al (2014). The full description of the alternative inventory methods can be found in Alvarez et al supplementary materials section S1.4. The alternative inventory resulted in an emission estimate of 8.8 Tg CH_4 for Petroleum and Natural Gas Systems, substantially lower than the primary estimate based on site- level data and validated with basin-level data.

Both the Alvarez et al alternative inventory and GHGI are thought to underestimate emissions due to limitations of the component-level approach. The positively skewed distribution of O&G component emission rates makes it likely that EFs based on the arithmetic mean of limited measurements will underestimate the mean emission rate of the full population. Additionally, site- level estimates based on the aggregate of component-level measurements tend to be biased low because some emissions sources may be overlooked, misquantified, or unsafe to measure. As described in Alvarez et al (2018),

> *Consequently, the most likely hypothesis for the difference between the EPA GHGI and BU [bottom-up] estimates derived from facility-level measurements is that measurements used to develop GHGI emission factors under-sample abnormal operating conditions encountered during the BU work. Component-based inventory estimates like the GHGI have been shown to underestimate facility-level emissions, probably because of the technical difficulty and safety and liability risks associated with measuring large emissions from, for example, venting tanks such as those observed in aerial surveys.*

For each segment, we discuss specific examples of how the GHGI underestimates emissions.

For the production segment, a previous study based on Barnett Shale data, Zavala-Araiza et al (2017), compared facility-level estimates derived from site-based measurements and aggregate, component-based estimates. Site-based estimates were 50% higher than component-based estimates, with the largest discrepancy found in the highest emitting sources. This gap was attributed primarily to abnormal process conditions that cause high emission rates, such as separator malfunctions that lead to irregular storage tank emissions. This hypothesis is supported by Lyon et al (2016), which used aerial infrared camera surveys of over 8,000 well pads in 7 basins to identify high emitters: tanks accounted for over 90% of these sources, and in several basins, occurred at a greater frequency than expected from normal emissions like tank flashing; in contrast, no large emissions were identified from sources like pneumatic controllers or connector leaks.

Therefore, it is likely that much of the GHGI underestimate is attributable to missing, large sources that are difficult to observe, categorize, and quantify.

For the gathering and boosting (G&B) segment, which the GHGI classifies as a sub-category within the Natural Gas Systems production segment, EPA currently estimates G&B station emissions with facility-level emission factors from Marchese et al (2015). That study estimated 2012 U.S. G&B station emissions were 1,697 (+189/−185) Gg CH_4 based on site-level measurements at 114 stations published in Mitchell et al (2015). The 2018 GHGI estimates 2016 G&B station emissions were 1,968 Gg CH_4 based on the Marchese et al EFs and updated station counts. Alvarez et al estimates 2015 G&B station emissions were 2,100 Gg CH_4 based on a similar approach to the GHGI, but with an updated EF based on a recalculation of Mitchell et al data with a log-normal distribution that accounts for high-emitting facilities above the sampled emission rate.

For the processing segment, the 2018 GHGI uses GHGRP data to estimate 2015 processing plant emissions were 410 Gg CH_4. As discussed in the stakeholder feedback previously submitted by EDF and Colorado State University (CSU) in 2017 to on *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Updates Under Consideration for Natural Gas Systems Processing Segment Emissions*, **we believe this approach underestimates emissions due to methodological issues associated with the GHGRP**. In our feedback, we proposed using an alternative approach that uses facility-level data from Marchese et al and Mitchell et al, which includes site-level measurements from 16 processing plants, to estimate total emissions. GHGRP data could be used to allocate total emissions among sources as a best approximation of source-specific emissions. Alvarez et al estimates 2015 processing plant emissions are 680 Gg CH_4 using an analogous approach with an updated processing plant EF based on a recalculation of Mitchell et al similar to the approach described above for G&B stations.

For the transmission and storage (T&S) segment, the 2018 GHGI estimates 2015 station emissions were 1,100 Gg CH_4 based on partial data from Zimmerle et al (2015), which used component- and site-level measurements from 45 stations measured in Subramanian et al (2015). The 2018 GHGI underestimates T&S emissions by excluding a substantial portion of observed emissions from Zimmerle et al that were classified as super-emitters/uncategorized. This category represents emissions that were quantified by site-level measurements but missing from aggregate component- level measurements due to known issues such as very high emission rate sources that are difficult to quantify at the component level – a phenomenon that was directly observed in these studies. In contrast, Alvarez et al estimates 2015 T&S station emissions were 1,540 Gg CH_4 because it included the 440 Gg from these uncategorized sources.

2. Component-level data such as the GHGRP should not be used to estimate total emissions unless emissions are validated with empirical site- and basin-level data

As discussed in Alvarez et al, emission estimates based on site- and basin-level measurements consistently show that component-based estimates underestimate emissions. While component- based estimates are valuable for understanding the approximate allocation of emissions among sources, they are not suitable for estimating total emissions without the support of other empirical data, because (as discussed above on page 2) component-level studies under-sample abnormal operating conditions which are responsible for a very substantial portion of real emissions.

Therefore, relying on component-level GHGRP data to estimate total emissions likely cause the GHGI to underestimate emissions from Natural Gas and Petroleum Systems.

For future years of the GHGI, EPA should improve the accuracy of their emission estimates by incorporating more empirical data including facility- and basin-level. As discussed in the National Academy of Science's report Improving Characterization of Anthropogenic Methane Emissions in the United States, verifiability is the key to an accurate, high quality inventory. For example, spatially gridding the GHGI can allow a comparison to basin-level estimates, but the utility of gridding the current GHGI is limited by the spatial resolution of certain GHGI / GHGRP data which aggregates emissions from all facilities owned by an operator in an AAPG basin. To make better use of site-level data, EPA should consider updates to the GHGI and GHGRP when the current format does not allow a straightforward estimate of region-specific, facility EFs. In particular, the GHGRP methodology for the G&B segment would benefit from updates that allow basin-level emissions to be disaggregated to the facility-level. By reorganizing the GHGI and underlying data such as the GHGRP to be verifiable at the site- and basin-level, EPA could use existing and future empirical data to test the accuracy of the inventory. When inaccuracies are discovered, EPA could use empirical data to adjust the GHGI emission estimates and/or focus future efforts on improving methodologies for the sources or regions with the largest discrepancies. A more inclusive use of empirical data from multiple spatial scales will allow EPA to more accurately understand Natural Gas and Petroleum Systems methane emissions.

Response: **The natural gas and petroleum emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the Inventory are consistent with current industry practices. The EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.**

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held a stakeholder workshop on greenhouse gas data for oil and gas in October of 2018, and webinars in June of 2018 and February of 2019. EPA released memos detailing updates under consideration and requesting stakeholder feedback. Stakeholder feedback received through these processes is discussed in the Recalculations Discussion and Planned Improvements sections below.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the Inventory. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of Inventory estimates. In the past few years, EPA has reviewed and in many cases, incorporated data from these data sources. The second type of study can provide general indications on potential over- and under-estimates. A key challenge in using these types of studies to assess Inventory results is having a relevant basis for comparison (i.e., the independent study should assess data from the Inventory and not another data set, such as EDGAR.). In an effort to improve the ability to compare the national-level inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1° x 0.1° spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization. The gridded methane inventory is designed to be consistent with the 2016 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014 estimates for the year 2012, which presents national totals.

Commenter: Interstate Natural Gas Association of America

Sandra Snyder

Docket ID Number: EPA-HQ-OAR-2018-0853-0005

Comment 20: In November 2018, EPA released a document[8] (the "November 2018 memo") describing potential updates to the annual inventory report, including proposed updates to the methane emission factor for transmission pipeline blowdowns based on 2016 data submitted under Subpart W of the GHGRP. EPA amended Subpart W to add reporting of transmission pipeline blowdown emissions by event type, and 2016 was the first reporting year. EPA was made aware of several issues regarding the November 2018 memo: erroneous data reported by one company in 2016 significantly affected the pipeline blowdown emission factor; the company had corrected the error and updated 2016 data were available; and, 2017 GHGRP data were also available for consideration. In the Draft Inventory Report, EPA addressed this problem by developing a transmission pipeline blowdown emission factor that averages the Subpart W data from 2016 and 2017, and applied the emission factor for the entire time series. EPA requested feedback on whether year-specific emission factors should be applied for 2016 and 2017, and whether the current emission factors should be applied for earlier years of the time series.

INGAA welcomes EPA's efforts to utilize data from Subpart W to improve methane emission estimates in the annual inventory report for the natural gas transmission and storage sector.

However, INGAA recommends alternatives for applying the 2016 and 2017 pipeline blowdown data and for subsequent annual inventory reports. INGAA's review of the historical / previous emission factor used for the annual inventory and more current data indicates that an emission factor based on 2016 Subpart W pipeline blowdown data is marginally higher than the previous emission factor, while an emission factor based on 2017 Subpart W pipeline blowdown data is approximately the same as the previous factor. Details are not provided in the Draft Inventory Report, but a summary based on INGAA's review indicates:

- The November 2018 memo presents the previous pipeline blowdown emission factor: 0.6 metric tons (mt) methane per mile of pipe (mt/mi).
- The November 2018 memo proposed increasing the emission factor to 1.2 mt/mi, but this emission factor included the erroneous 2016 data.
- The Draft Inventory Report proposes to average the 2016 corrected data and 2017 data, and INGAA's review indicates that emission factor is 0.72 mt/mi.
- The emission factor based on 2017 data is 0.61 mt/mi.
- The emission factor based on 2016 data is 0.84 mt/mi.
- The event-specific information indicates that 2016 Subpart W data showed higher emissions and events than 2017 data for new construction or modification (including commissioning) and equipment replacement or repair. Higher emissions from those event types may not be typical or representative of other years.

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[8] "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017: Other Updates Under Consideration," U.S. EPA (November 2018).

In response to EPA's request and in light of the differences in 2016 and 2017 data, INGAA recommends using year-specific emissions for 2016 and 2017, and applying the historical/previous emission factor for the earlier years in the time series. The resulting time series would show a one- year increase in emissions in 2016 and similar emissions for other years. Alternatively, EPA could refrain from updating the emission factor in the 2019 inventory report, gather an additional year of Subpart W data, and update the transmission pipeline blowdown emission factor and emission estimates in the 2020 annual inventory report. The third year of Subpart W data (for 2018) could provide insight regarding year-to-year variability and whether any data appears to be anomalous. For example, data quality associated with the first year of reporting (or higher than typical construction and equipment replacement events) could indicate that 2016 is not representative of typical natural gas transmission pipeline operations.

Response: We agree with the comment and have updated the final GHGI to use year-specific GHGRP data for 2016 and 2017 emissions and GRI/EPA 1996 data for 1990-2015 emissions. We plan to review 2018 (and future years) GHGRP data to update the time series, assessing year-specific factors or other options such as average factors.

Commenter: National Association of Clean Water Agencies

Cynthia Finley, Ph.D.

Docket ID Number:

Comment 21: The National Association of Clean Water Agencies (NACWA) has submitted comments on the wastewater treatment section since the 2005 Inventory, and we appreciate the clarifications that EPA has made over the years for the emissions calculations and the factors that are used in the calculations. Several references were updated in the 2017 Inventory to better reflect current characteristics of the sector. However, more work needs to be done on updating data sources. For example, the outdated 2004 Clean Watershed Needs Survey (CWNS) was still used as the basis for the percent of wastewater flow to aerobic and anaerobic systems, the percent of utilities that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters. The forecasts made using the 2004 CWNS and previous editions of the CWNS may not accurately reflect recent trends and practices for wastewater utilities.

NACWA agrees with EPA's planned improvement to investigate updated sources and re-evaluate its methodology as related to wastewater system type and methane emissions.

Response: EPA continues to search for and review updated sources of activity data for wastewater treatment system type to distinguish between aerobic, anaerobic, and aerobic systems with the potential to generate CH4. Due to significant changes in format, CWNS data for 2008 and 2012 require additional evaluation to determine a methodology for incorporation into the Inventory. In addition, other data continue to be evaluated to update future years of the Inventory, including anaerobic digester data available at biogasdata.org. EPA will continue to monitor the status of these data as a potential source of digester, sludge, and biogas data from POTWs.

Comment 22: Another factor that should be updated is the wastewater flow of 100 gal/person/day, which was taken from a 2004 document published by the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. Due to droughts and effective water conservation measures, many areas of the US now have wastewater flows significantly less than this value. NACWA recommends that EPA consider updated wastewater flow references that represent other regions of the country.

Response: EPA continues to search for and review updated sources of activity data, including improved data on the amount of biogas generated in anaerobic digesters. EPA will continue to monitor the status of data available from biogasdata.org as a potential source of biogas generated from anaerobic digesters, which would obviate the need to use the estimated wastewater flow of 100 gal/person/day.

Comment 23: NACWA agrees with EPA's planned improvements for the Inventory and encourages development of US-specific methodologies and emission factors when appropriate. As NACWA has explained in comments on the Inventory in previous years, the Association believes that the nitrogen loading rates for $N_2O_{EFFLUENT}$ are sourced incorrectly and that using information from the existing National Pollutant Discharge Elimination System (NPDES) database will yield more accurate and justifiable loading rates. The NPDES permitting program represents long-term, nationwide facility performance that would allow emissions estimate projections over the time series represented in the Inventory. EPA should also investigate additional references for nitrogen loading rates.

Response: EPA has considered NACWA's suggestion to estimate nitrogen effluency loads based on data reported under EPA's National Pollutant Discharge Elimination System (NPDES) Program. Unfortunately, very few POTWs are required to report their effluent nitrogen concentration or load, and those that do are typically required to meet more stringent limits that the average POTW. At this time, EPA is unable to confirm that these data would be representative of the entire industry. In addition, this would represent a departure from the IPCC accepted methodology and would require substantiation that it results in a more robust estimation of these nitrous oxide emissions.

Comment 24: As EPA notes in the Inventory, the refinements to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* – which are currently undergoing government review – may incorporate newer scientific information. The IPCC's refinement of the emissions factors used in wastewater treatment emissions calculations may resolve some of the issues with the current methodology. Since the refinements will not be available for public review and comment prior to publication, NACWA asks that EPA allow additional time for expert review when the refinements are incorporated into the Inventory for the first time.

Response: EPA agrees that the potential refinements to the 2006 IPCC Guidelines will inform how the methodology may need to be revised. EPA continues to evaluate potential new data sources to update and improve the Inventory data as they become available, including improved activity data on wastewater treatment operations as well as nitrogen loading rates. Addition data sources will continue to be researched with the goal of reducing uncertainty of the estimate of N entering municipal treatment systems, as well as the estimate of N discharged to receiving waters. EPA provides opportunities to review changes to the Inventory during expert review, typically from mid-October to mid-November of each year. And during the 30-day public review period, typically from mid-February to mid-March of each year. EPA then finalizes the Inventory for publication in April. EPA will ensure that NACWA is provided opportunity to comment during both review periods which should allow sufficient time for review of any changes made as a result of the refinements.

Commenter: National Cattlemen's Beef Association

Document ID Number: EPA-HQ-OAR-2018-0853-0006

Comment 25: While enteric fermentation from cattle composes a notable portion of methane emissions (26%), methane emissions are only a fraction (10.2%) of overall greenhouse gas (GHG) emissions that enter our environment. Cattle producers are frequently portrayed as one of our nation's top greenhouse gas emitters, when the Draft Inventory makes clear that beef production falls behind transportation, electricity generation, refrigerants, and myriad other emission sources. The Draft Inventory posits that agricultural emissions contribute 8.4% of all GHG emissions, with agricultural soil management, enteric fermentation, and manure management systems contributing the most to this percentage. NCBA appreciates the Agency's attempt to reach science-based conclusions and notes some areas where the Agency can further bolster its Inventory. Specifically, for these comments, NCBA will focus on EPA's enteric fermentation calculation and analysis.

The Draft Inventory is littered with assumptions left unsubstantiated in the academic record. The Draft Inventory provides, at best, hollow analysis for its conclusion that, although the Agency ties enteric fermentation emissions to U.S. beef cattle population, and the beef cattle population decreased from 1990 to 2017, enteric fermentation emissions did not correlate. To substantiate its claim that EPA enteric fermentation from beef cattle has increased by 6.1 percent in the last 27 years, EPA cites five instances of "personal communication." Though EPA includes a scarce list of citations, the studies referenced show that the primary contributors of enteric fermentation emissions are not grain fed cattle. However, the Agency's rhetoric in preparing the Draft Inventory suggests differently: "Beef cattle emissions generally increased from 2004 to 2007, as beef cattle populations underwent increases and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years." While perhaps unintended, the Agency's focus on feedlot cattle populations leads readers to conclude that grain fed cattle are the primary contributor to enteric fermentation emissions, when EPA's referenced studies conclude otherwise. At minimum, NCBA urges EPA to better contextualize these statements.

The Draft Inventory bases its methane emissions estimates from enteric fermentation on the United Nation's model found in the Intergovernmental Panel on Climate Change's Guidelines for GHG Inventories. However, this model is unusable according to the Agency's own standard. In the Draft Inventory's introduction, the Agency states that it will use emissions calculators from the EPA or other U.S. governmental agencies. The United Nations IPCC model does not meet this criterion. A national source-specific model will likely provide more accurate data than a broad, international model. NCBA suggests that the Agency consider adopting the Integrated Farm System Model, used in a recently published USDA ARS-led beef lifecycle assessment.[9] The published lifecycle assessment considers all inputs, including electricity use and transportation, a notably different approach than the EPA Draft Inventory. However, the Integrated Farm System Model can be tailored to exclude these inputs. Nevertheless, USDA's beef lifecycle assessment is vital to the Inventory and NCBA urges EPA to include it in the final Inventory.

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[9] C.A. Rotz, B.J. Isenberg, K.R. Stackhouse-Lawson, J. Pollak, *A Simulation-Based Approach for Evaluating and Comparing the Environmental Footprints of Beef Production Systems*, J. Anim. Sci., 91 (2013), pp. 5427-5437; C.A. Rotz, S. Asem- Hiablie, S. Place, G. Thomas, *Environmental Footprints of Beef Cattle Production in the United States*, Agricultural Systems, 169, pp. 1-13.

NCBA is pleased with the Agency's effort to recognize existing GHG emission offsets. The Agency has attempted to do this for the first time by calculating benefits gained from carbon sinks. As the Agency noted in its previous GHG inventory, carbon sinks account for a 20% offset of agricultural GHG emissions – significantly reducing the net impact of the industry. NCBA encourages the bolstering of this section generally, so that regulated stakeholders and consumers alike can assess the net impact of GHG emitters. Going forward, NCBA urges EPA to specifically consider the environmental benefit of planned rotational grazing, a conservation practice implemented by ranchers across the country. It is well-known that rotational grazing leads to increased carbon sequestration.[10] Globally, if soil organic carbon in agricultural lands and grasslands increase 10% over the course of the 21st century, carbon dioxide concentrations in the atmosphere could be reduced by 110 ppm.[11]

<u>Response</u>: EPA appreciates the commenter's suggestions on the emission calculations and analyses conducted for the Enteric Fermentation source category of the Public Review draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017 (Inventory). The EPA works closely with partners including USDA, other government agencies, academia and consultants to develop the best estimates using the best available data.

As described in the Chapter 5.1 and Annex 3.10 of the Inventory, the enteric fermentation emissions are estimated using EPA's Cattle Enteric Fermentation Model (CEFM). The CEFM is a national, source-specific model whose calculations are based upon Intergovernmental Panel on Climate Change (IPCC) Tier 2 methodology for cattle, which is a detailed approach that involves national, regional, and state-level data for the U.S. cattle sector.

Beef cattle populations are one of many variables of data used to estimate emissions. Additional variables that influence emissions estimates are feed digestibility and animal weight. As a result, and noted within the trends discussion of Chapter 5.1, population decreases alone do not necessarily result in a decrease in enteric fermentation emissions for that population.

The Inventory categorizes methane emissions by type of beef cattle in Annex Table A-178, where emissions by feedlot cattle, steer stockers, heifer stockers, and replacements are reported. Furthermore, Annex Table A-175 provides the methane emission factors for cattle by animal type. This table demonstrates the higher emissions associated with a less-digestible diet from stockers when compared to feedlot cattle. The Annex presents additional information utilized in the emissions calculation such as the percent of digestible energy in feed for different beef types and changes in population broken out by type of beef livestock over time, as well as a breakdown of emissions.

EPA consults with experts in the field of beef cattle production to help inform the data variables used in estimating emissions, citing these as "expert judgement" or "personal communications" within the Inventory. This is a common practice for Inventory compilation that is necessary because the data required to estimate emissions are not always available in publications. Within the Inventory, discussion and values for emissions trends over time are based directly on results from the CEFM, which derives its inputs from the data sources cited in the chapter. We welcome additional data to improve future Inventory estimates, and EPA and USDA would like to work with NCBA and other

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[10] Wang, T.; Teague, W.R.; Park, S.C.; Bevers, S. *GHG Mitigation Potential of Different Grazing Strategies in the United States Southern Great Plains*. Sustainability, 7 (2015), pp. 13500-13521.

[11] Lal, R., *Sequestering carbon in soils of agro-ecosystems*. Food Policy. 36 (2011), (Suppl. 1): S33-S39.

stakeholders to learn about any other data available that could contribute to future Inventory estimates.

EPA and USDA are currently reviewing many data sources and improvements that could be used in future Inventory reports. Many of these improvements will require significant effort and may take multiple years to implement in full. As part of the overall improvement process within the Agriculture chapter, EPA and USDA held a data workshop in March 2018 with industry and researchers to assess the availability of activity data that could be used in the Inventory to better inform us of current industry practices. Once incorporated, these updates will improve the Inventory estimates by better reflecting recent trends in farm management. Potential improvement options that EPA is considering are currently listed in the Planned Improvements section of Chapter 5.1.

Commenter: Waste Management, Republic Services, National Waste & Recycling Association, Solid Waste Association of North America, SCS Engineers, Weaver Consulting Group

Amy Van Kolken Banister

Docket ID Number: EPA-HQ-OAR-2018-0853-0004

Comment 26: The waste sector strongly supports the Agency's efforts thus far to update the inventory, and we are pleased that EPA intends to continue its dialogue with stakeholders, academic researchers and landfill experts. We think this is important work and we are particularly pleased that EPA is planning on considering improvements in the Inventory's assumed DOC value, and decay rates used in estimating methane generation at landfills and recognizes the need to update those factors in the Greenhouse Gas (GHG) Reporting Rule.

<u>The Scale-Up Factor for MSW Landfills</u>

Recognizing that the GHG Reporting Program (GHGRP) does not include every MSW landfill in the country – (MSW landfills that ceased taking waste prior to 1980 or have potential emissions less than 25,000 tons CO_2e) – we continue to support EPA's decision to use a scale-up factor to estimate emissions from non-reporting landfills in the draft 1990-2017 Inventory. As part of the expert review of the draft 2018 Inventory, the landfill sector reviewed the largest of the Agency's list of potential landfills not reporting emissions to the GHGRP. We found that the Agency overestimated Waste in Place (WIP) by more than 60 percent and recommended adjusting the scale-up factor to 5 percent from 12.5 percent. We were pleased that EPA adjusted the factor for the 2018 Inventory and employed a lower scale-up factor of 9 percent; however, adjusting the scale-up factor to a lower, more appropriate value could be reflected in the 2019 Inventory as the analysis of non-reporting landfills has been accomplished. **We thus recommend that EPA consider using an even lower factor of five percent before finalizing the 2019 Inventory.**

Further, EPA should evaluate and revise the scale-up factor on a routine basis to account for the additional WIP for sites reporting to GHGRP which is likely to significantly exceed non- reporting facilities that have closed and are no longer receiving waste. The Agency can reasonably anticipate a downward trend in WIP at landfills outside the GHGRP, and the scale-up factor should reflect these changing landfill demographics.

Response: EPA appreciates commenter's support of the scale-up factor approach to account for landfills that do not report to the GHGRP. EPA also appreciates and agrees with the commenter's feedback that the scale-up factor should be evaluated on a routine basis. EPA plans to reexamine the scale-up factor with each inventory cycle to determine if there are additional landfills reporting to the GHGRP such that the WIP assumed for those landfills can be removed from the scale-up factor. At the same time, EPA will also account for those landfills that have stopped reporting to the program because they were able to exercise the off-ramp provisions.

Comment 27: <u>Methane Oxidation Factor</u>

For the period 1990 – 2004 in the inventory time series, EPA calculates a national estimate of methane generation and emissions using a combination of secondary data sources that detail the annual quantity of waste landfilled and the annual quantity of methane recovered from facilities with landfill gas collection and control systems. EPA applies a 10% oxidation factor to all facilities for the years 1990 to 2004. This ten percent default factor contrasts significantly with the average methane oxidation factor of 19.5 percent applied through use of GHGRP data, to the later years of the time series (2005 to 2016). Importantly, the 19.5 percent average oxidation rate incorporated in the GHGRP, subpart HH emissions data is premised on a more detailed and up-to-date estimation approach than is the default value of 10 percent. It is also a conservative average value, as the GHGRP methodology restricted the maximum oxidation rate to 35 percent.

In its work to review and revise the method for calculating methane oxidation under subpart HH of the GHGRP, EPA acknowledged the need to update the default 10 percent oxidation value. The default value was based on only one field study, at a landfill without gas collection and control, and did not reflect the much higher oxidation values found in numerous subsequent, peer-reviewed field studies. **Given the plethora of scientific studies showing methane oxidation to be several times higher than the EPA and Intergovernmental Panel on Climate Change (IPCC) default value, we strongly recommend EPA apply a revised value (perhaps the average oxidation value from the GHGRP) to the earlier years of the time series.**

Response: EPA appreciates commenter's feedback on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017. As stated in the Planned Improvements section of Section 7.1 of the Inventory, EPA is continuing to review new literature and investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as a the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2017) averages to 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.

Comment 28: <u>Compost Emission Factor</u>

In ideal conditions, the composting process occurs at a moisture content of between 50 and 60%, but the moisture content of feedstocks received at composting sites varies and can range from 20% to 80%. It is common for moisture to be added to dry feedstocks prior to the start of composting to optimize the biological process. In the calculation of emissions from composting in the draft chapter, it appears that all incoming wastes were assumed to have a moisture content of 60%. If 60% is not reflective of the actual weighted average of all feedstocks, this will introduce errors in the inventory calculation that could be significant.

We recommend that the calculations be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents, or ask that further information to be provided on the rationale for assuming 60% as the average moisture content of all inbound materials.

Response: EPA notes commenter's feedback on the moisture content levels used in the calculation of emissions from composting. The calculations for composting are based on IPCC Tier 1 methodology defaults. Under this methodology, the emission factors for CH_4 and N_2O assume a moisture content of 60% in the wet waste. (IPCC 2006). EPA has added this detail to the Methodology section of Section 7.3 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017 so that the source of the moisture content is more transparent. In addition, EPA has added to the Planned Improvements section of Section 7.3 that EPA is looking into the possibility of incorporating more specific waste subcategories and category-specific moisture contents into the emissions estimates for composting in the United States to improve accuracy. However, to date the EPA has not been able to locate substantial information on the composition of waste at U.S. composting facilities in order to do so. As additional data becomes available on the composition of waste at these facilities, EPA will consider using this information in order to create a more detailed calculation of U.S. composting emissions.

Comment 29: The k Factor (Methane Generation Rate Constant)

The waste sector strongly supports EPA's plans to assess using k values based on climate and recommends that the Agency review the k-values against new data and other landfill gas models, as well as to assess the uncertainty factor applied to these k values in the Waste Model. We have been concerned that these k-values are outdated and rife with uncertainty, as confirmed by the *Draft AP 42.2.4 Municipal Solid Waste Landfills*, which states:

> *There is a significant level of uncertainty in Equation 2 and its recommended default values for k and L_o. The recommended defaults k and L_o for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH_4 emissions that ranged from ~30 to 400% of measured values and had a relative standard deviation of 0.73 (Table 2-2). The default values for wet landfills were based on a more limited set of data and are expected to contain even greater uncertainty.*[12]

The waste sector has previously highlighted the significant issues with the k values used in the Draft AP-42 Section 2.4: Municipal Solid Waste Landfills. In fact, EPA has never finalized AP-42 for MSW landfills, despite the k-value issues identified *by EPA* in both AP-42 and the Background Information Document. With uncertainties in CH_4 emissions ranging from -30% to 400% under EPA's assessment of the Landfill Gas Emissions (LandGEM) model, it is difficult to rely on these data. For this reason, we support EPA's plan to review and resolve the significant problems in the k value data set.

Response: EPA appreciates commenter's support for planned improvements outlined in the report. As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA began investigating the k values for the three climate types (dry, moderate, and wet) against new data and other landfill gas models, and how they are applied to the percentage of the population assigned to these climate types. EPA will also assess the uncertainty factor applied

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[12] U.S. EPA, *Draft AP 42.2.4: Municipal Solid Waste Landfills*, October 2008, p. 2.4-6.

to these k values in the Waste Model. Like the DOC value, the k values applied through the Waste Model are for the years 1990 to 2004; the k values for 2005 to 2017 are directly incorporated into the net methane emissions reported to EPA's GHGRP. EPA will continue investigating the literature for available k value data to understand if the data warrant revisions to the k values used in the Waste Model between 1990 to 2004.

Comment 30: Degradable Organic Carbon (DOC)

Chapter 7 of the draft inventory explains that EPA uses one DOC value of 0.20 to calculate emissions for the years 1990 through 2004, and uses emissions reported through the GHGRP for years 2005 through 2017. The GHGRP allows landfills to use 0.20 for bulk MSW or allows a landfill to further delineate waste streams by accounting for separate shipments of construction and demolition (C&D) waste, which uses a DOC of 0.08, and separate shipments of inert wastes, which may use a DOC of 0.0. If a landfill delineates in this way, it must use a DOC of 0.31 for its MSW waste volumes, which applies an artificially high DOC to MSW, and inappropriately overestimates emissions. The required DOC value of 0.31 fails to account for the significant volumes of C&D and inert wastes that are incorporated in MSW, and which cannot be separated from the MSW or accounted for distinctly, as can discrete shipments of inert wastes from industrial or C&D recycling facilities. Furthermore, neither of the EPA- recommended DOC guidelines have been reviewed in many years. **We therefore support EPA's view that it is time to update the DOC values and believe that the most valuable focus would be to reassess the DOC values incorporated in the GHGRP used for inventory years 2005 forward.**

We are pleased to learn that EPA plans to revisit the DOC value of 0.20, and as we discussed with you, **we strongly recommend focusing first on the later portion of the time series.** We believe that the fundamental shifts in the characterization of waste disposed in landfills has occurred in the later portion of the time series and that the research conducted thus far by state agencies and the Environmental Research and Education Foundation (EREF)[13] are illustrative of those changes. **We also recommend that as EPA revises DOC values used in the second half of the time series the Agency should as a priority, also reevaluate and accordingly revise the DOC values incorporated in subpart HH of the GHGRP, which underpins the data used for those years of the inventory.**

Based on EREF's review of the DOC values for MSW landfills, the waste sector concludes that the long-standing DOC values developed in the past are inaccurate and are likely to over- estimate both landfill gas generation and methane emissions. The data provided by EREF confirms that two trends are driving the changes at MSW Landfills. First, many MSW Landfills are handling less organic matter now, and this trend is anticipated to continue due to state and local organics diversion goals. Second, the increase of Subtitle D non-MSW waste disposed has altered the DOC for all waste deposited in MSW Landfills. EPA validates these trends in the Inventory's Chapter 6 discussion of carbon sequestration of harvested wood products, yard waste and food waste, which shows a significant reduction in sequestered carbon since 1990 due to reduced volumes of organic wastes disposed in landfills.

Further, as EPA clearly recognizes that the composition of the waste at MSW Landfills has changed and continues to change, we suggest the Agency add an additional factor, "(5) the composition of the waste" to the sentence on line 42, page 7-2 of the waste chapter that begins: "Methane generation and emissions from landfills are a function of several factors."

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[13] Staley, B.F. and Kantner, D.L., Estimating Degradable Organic Carbon in MSW Landfills and the Impact of Non-MSW Materials, EREF – Environmental Research and Education Foundation, 2016, Table 1, p.4

Response: EPA appreciates commenter’s support for planned improvements outlined in the report. As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA currently uses one value of 0.20 for the DOC for years 1990 to 2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide). EPA also notes the recommendation from the commenter regarding the DOC values used in the GHGRP, in the context of new information on the composition of waste disposed in MSW landfills; these newer values could then be reflected in the 2005 and later years of the Inventory. EPA is continuing to investigate publicly available waste characterization studies and calculated DOC values resulting from the study data.

Commenter: Private Citizen (Isaiah)

Isaiah

Docket ID Number: EPA-HQ-OAR-2018-0853-0003

Comment 31: I feel as if we are overlooking a major problem that is occurring to our environment and not enough regulations are being made to fix this. Greenhouse gases and the change in climate is destroying our environment little by little and by the time these problems start affecting us it will be too late. Ocean acidification and the icebergs melting cannot be solved through money or passing a law. We have to change the whole mindset of our country and instead of focusing on wars in Iran or how Korea will bomb us we should be focusing on the war against pollution and how our ocean will harm us. Instead of being worried about being reelected focus on the impact you will leave for the future generation.

Response: EPA appreciates the commenter’s interest in the annual development of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017. These comments are noted but are out of scope of this review.

Commenter: Private Citizen (Matthews)

Mark Matthews

Comment 32: I am concerned that the estimates of the release of methane gas from the processing of coal are not being fully captured. Section 3.4 seems to be saying that the only methane emissions being counted from the post-mining processing and storage of coal involves the kind of bulk crushing of coal that occurs at a mine site before it is transported (usually by train) to a power plant, and where it sits in waiting to be burned at the power plant. All the off-gassing of methane up to that point is being counted. BUT before the coal is burned it is usually further crushed to a very small size before it is actually fed into the burner. It doesn't appear that the release of methane from this process is being counted. According to Diamond and Schatzel (see below) this kind of processing releases the "residual" methane content of the coal and this "residual" is 40 to 50% of the total methane content of the coal. In other words, the total off-gassing of methane from post-mining processing could be twice as much as has been estimated. It could be even higher since some coals can take "months" to degas from even bulk crushing - so if the coal retains its methane tightly and it is sent to the plant quickly (within days or weeks) and burnt shortly after it arrives (it's my understanding that they don't typically keep huge inventories of coal at the plant, so it may be burnt within days or a week) then the vast majority of its methane content may be released by pulverization at the plant. Is this release being inventoried?

> *From: Measuring the gas content of coal: A review William P. Diamond, Steven J. Schatzel (International Journal of Coal Geology 35(1):311-331, February 1998)*
>
> *"The volume of gas desorbing from a coal sample gradually declines with time. Desorption measurements for the extended desorption techniques are terminated at some point when an arbitrary low desorption rate is reached. This rate may be reached in a matter of days for very Mable samples or can take months for some blocky coals. Generally, when the desorption rate reaches an established termination point, some volume of gas remains in the sample. Traditionally, this residual gas has been thought of as gas that is 'trapped' within the coal structure due to slow diffusion rates. Bertard et al. (1970) and Levine (1992) suggest that the residual gas may not be diffusion dependent, but in part, represents gas remaining in equilibrium under approximately 1 atm of methane pressure in the desorption canister. The residual gas volume can be determined by crushing the sample in an airtight container and measuring the volume of gas released by the same method as that used for the desorbed gas (Diamond et al., 1986). The volume of residual gas measured in the laboratory for samples subjected to elevated temperatures to approximate actual reservoir conditions will probably be less than would have been measured if the sample had equilibrated to ambient laboratory temperature during desorption monitoring.* ***Analysis of the gas content component parts for 1,500 coal samples from 250 coalbeds in the United States (Diamond et al., 1986), shows that residual gas can comprise 40 to 50% of the total gas content,*** *in particular for relatively low-rank (high volatile-A bituminous) blocky coalbeds"*

Response: The article cited by the commenter (Diamond and Schatzel, 1998) estimates that the residual methane content of coal after mining ranges from 10 to 50 percent of the total gas content of the coal. EPA uses an emission factor of 32.5 percent to account for methane desorption during coal transport and storage. This emission factor is based on Creedy (1993), which estimates that on average 40 percent of the in-situ gas content of coal remains after mining. This estimate in Creedy is based on gas emission prediction modeling and measured data. Creedy further assumes that this remaining methane content is emitted while the coal is in transit and during storage prior to combustion. The EPA believes that the mid-range emission factor currently used in the Inventory, based on Creedy, is generally consistent with the range of estimates of coal residual gas content presented in the article cited by the commenter. However, EPA will further review the article referenced by the commenter and consider whether adjustment of the emission factor for post-mining activities is warranted.

Other Comments

EPA received one additional anonymous technical public comment as part of the public review of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017*. This comment can be found on the public docket and is copied below.

Anonymous

Docket ID: EPA-HQ-OAR-2018-0853-0002

Comment 33: EPA must ensure that it is properly accounting for carbon dioxide emissions from wet flue gas desulfurization (FGD) systems at coal-fired power plants. Wet FGDs which use calcium carbonate and other agents can have significant CO2 emissions which are in addition to the CO2 emissions from the combustion of the coal.

Response: EPA includes and reports these emissions in Chapter 4 under Section 4.4 Other Process Uses of Carbonates which starts on page 4-20 of the report. The component of process uses of carbonates emissions associated with FGD is also reported as part of Electric Power Industry emissions in Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq. and Percent of Total in 2017) on page 2-14 of the report.

United States
Environmental Protection
Agency

Summary of Expert Review Comments and Responses:
Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017*

April 2019
U.S. Environmental Protection Agency
Office of Atmospheric Programs
Washington, D.C.

Responses to Comments Received during the Expert Review Period on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017*

Preface

EPA thanks all reviewers and commenters for their interest and feedback on the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks. To continue to improve the estimates in the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks, EPA distributed draft chapters of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017* for a preliminary Expert Review of estimates and methodological updates prior to release for Public Review. The Expert Review was 30 days by sector and included charge questions to focus review on methodological refinements and other areas identified by EPA as needing a more in-depth review by experts. The goal of the expert review is to provide an objective and independent review of the Inventory to ensure that the final Inventory estimates, and document reflect sound technical information and analysis.

EPA received 54 unique comments on as part of the expert review process. The verbatim text of each comment extracted from the original comment letters is included in this document, arranged by sectoral chapters. No comments were received on the Draft Land Use, Land-Use Change, and Forestry Chapter. EPA's responses to comments are provided immediately following each comment excerpt. The list of reviewers, dates of review and all charge questions distributed to reviewers are included in the Appendix to this document.

Chapter 3. Energy

Comment 1: Clarity and Transparency of the Energy Chapter
Within the source categories, the information is generally clear and adequately sourced. However, missing from the chapter draft is a front-end section outlining the specific source categories to be discussed.

Response: As discussed in the Expert Review draft chapter and review memo, only some emission sources were updated for the Energy chapter. The remaining source categories of the Energy chapter were updated later. The sections that were not updated were removed from the Expert Review draft report for purposes of facilitating review. The front section was updated and included for Public Review as well as for the Final Report.

Comment 2: Completeness and/or Accuracy of the Energy chapter
Previous versions of the Sinks and Sources report have had a high-level summary at the front of the chapter that significantly improved readability and laid a general framework around which to think about emissions from energy, pulling forward some of the high-level findings and general discussion about the impact of energy use on emissions. It is not clear why that is removed from this draft chapter, but I would recommend the Agency continue to include those high-level findings before diving into the source categories.

Response: As discussed in the Expert Review draft chapter and review memo, only some emission sources were updated for the Energy chapter. The remaining source categories of the Energy chapter were updated later. The sections that were not updated were removed from the Expert Review draft report for purposes of facilitating review. The front section was updated and included for Public Review as well as for the Final Report. A linked Table of Contents was provided in the Expert Review draft for ease of review and to allow expert reviewers to focus on only their specific areas of interest.

3.1 Fossil Fuel Combustion

Comment 3: Monthly Vehicle Sales – Methodology for Estimating Electricity Use by On-Highway Electric Vehicles
The available monthly data from hybridcars.com is a reasonable estimate for data to-date and comes from Baum and Associates. However, that data is no longer being updated as of June 2018. The Alliance of Automobile Manufacturers also maintains its own public database (AAM 2018), using data from Polk/IHS-Markit. The only other public dataset of which I'm aware is that of insideevs.com; however, that data is extrapolated based on public information and may not necessarily represent an accurate accounting of current year sales data.

If the Alliance continues to update its data, EPA should avail themselves of it. Or, in the future EPA could consider acquiring an industry dataset to ensure reliable current year sales data, such as Polk-IHS or WardsAuto. One benefit of utilizing Polk-IHS data is that by examining current registration data, it would help solve one of the major sources of error in the Agency's current assessment—survivability.

The Agency's assumption of the electric fleet is that no vehicles sold since 2010 have been scrapped (p. 2). This is not a reasonable assumption. The National Highway Traffic Safety Administration (NHTSA) has previously estimated survivability data using the Polk National Vehicle Population Profile (NHTSA 2006). A recent paper on scrappage used a slightly narrower subset of that data in its own scrappage analysis (Jacobsen and van Benthem 2015). Using these sources, I estimate that the Agency's current process yields in 2017 an overestimated fleet size of 2.3-3.7% Car PHEVs, 2.0-3.3% Car BEVs, 1.2-1.4% LT PHEVs, and 1.4-1.6% LT BEVs. Correcting this issue well before 2025 (according to the cited 15-year lifetime) is highly recommended. While these national estimates of scrappage may not be perfect estimates of EV scrappage, it is likely that for early generations of EVs the scrappage rate could be even higher given the rapidly advancing technology and large number of leases offered for these products.

Response: We agree that the use of hybridcars.com has been a good data source for the 1990-2017 inventory, but given that this data source is no longer available, EPA intends to use data from insideevs.com for future Inventories. We will continue to assess availability of improved hybrid cars monthly vehicles sales information.

With regards to vehicle scrappage, we agree that a scrappage formula based on literature data will need to be applied in future inventories. We are still exploring studies related specifically to the scrappage of EVs. Any updates to reflect scrappage will be included in future expert reviews when completed.

Comment 4: Include Transportation as an end-use sector

Within the section on the Electric Power Sector (beginning on p. 3-9), it would be appropriate for the Agency to now include Transportation as an end-use sector in addition to Industrial, Commercial, and Residential, to reflect its new apportioning of "upstream" emissions from electric vehicles to the Transportation sector.

Response: Transportation is not included as an electricity end-use sector in Chapter 3 (e.g., Figure 3.9) because the amount of electricity allocated to Transportation is very small (even with the addition of electric vehicles), compared to the residential and commercial sectors. EPA does, however, report electricity emissions broken out by Economic End-Use Sector, including Residential, Commercial, Industrial and Transportation, in the report's Executive Summary and Chapter 2 (see, for example, Table 2-5 and Figure 2-8). Electricity use by end-use sector is also listed in Annex 2, Table A-43: Electricity Consumption by End-Use Sector (Billion Kilowatt-Hours), where it can be seen that electricity use in the transportation sector represents less than 1% of electricity sales in 2017. However, we acknowledge this is a category with changing trends, and will consider further disaggregation of electricity end-use sectors in future reports as growth trends continue.

Comment 5: VMT Statistics – Methodology for Estimating Electricity Use by On-Highway Electric Vehicles

As described in NHTSA 2006, it is generally true that newer vehicles travel more miles than older vehicles, in which case one would expect that using the national average VMT would result in a significant underestimate. On the other hand, one could expect that limitations on BEV range and different regional distribution of EV sales could depress that mileage estimate

For BEVs, a study of EVs in Arizona (EPRI 2018) yielded a wide range of results, with vehicles like the Focus and Smart Fortwo showing annual VMT much less than the assumed 11,300, while Tesla's EVs, which have a much larger range, showed average VMT significantly higher (nearly 15,000 miles). This is consistent with the idea that range plays some role in annual VMT and suggests that as more and more models achieve ranges on par with Tesla, BEVs would be expected to achieve annual VMT more similar to their gasoline-powered counterparts, which would be higher than the Agency's estimate (since the EV fleet will skew newer).

PHEVs should not suffer from range limitations, and that is borne out in the data. A detailed study of the PHEV Chevy Volt (Smart et al. 2013) showed VMT consistent with what one would expect for a brand-new vehicle (median = 31.6 miles/day → 11,500 annual; average = 40.7 miles/day → 15,000 annual). Similarly, EPRI 2018 showed a median mileage of over 12,000 miles, again higher than the Agency's estimate.

Importantly, relying upon the SAE utility factor (UF) likely underestimates the annual electric miles traveled by PHEVs. A study of early model Chevy Volts showed utilization 7-8% higher than would be expected based on the EPA charge-depletion range (Smart et al. 2014). EPRI 2018 showed utilization for its PHEVs at or well-above the SAE value (40% for a C-MAX Energi but 68% for a Fusion Energi and an average of 83% for the 23 Chevy Volts in the study, both well above the SAE UF). The SAE standard assumes only one charging event per day, while many Volts exhibited multiple charging events per day—it is unknown at this time how much of this behavior may be dependent upon unique characteristics of early adopters, but it is suggestive that the SAE UF represents a lower bound and therefore a conservative estimate of electric miles traveled by PHEVs.

Response: We acknowledge that both BEVs and PHEVs may have VMT that differ from the FHWA average VMT, however VMT from electric vehicles is not well studied or documented. While we agree with the literature that newer cars travel further than older cars, as an average with believe using the FHWA average is appropriate.

Comment 6: 85/15 Percent Allocation to Residential/Commercial Sectors – Methodology for Estimating Electricity Use by On-Highway Electric Vehicles

This is approximately consistent with EPRI 2018, which showed 83% of GPS-identified electric charging (by kWh) occurring at the home.

However, one fundamentally incorrect issue with the approach taken by EPA relates to the location of the charging event itself, i.e. the grid used. Electric vehicles are not uniformly distributed throughout the country and will not charge on the average national grid. More than half of the electric vehicles sold are sold in California (AAM 2018), which has a grid that is significantly cleaner than average (EPA 2018). Using data on EV sales through 2017, including losses related to transmission and distribution, I estimate that the average EV is charged at a rate of 355 g/kWh, compared to a national average of 477 g/kWh, a 25.5 percent reduction.[1]

EPA must consider regional distribution of electric vehicles in its assessment of emissions from these vehicles. This can be achieved by combining its latest eGRID data with sales information already recommended EPA obtain.

[1] To be more consistent with the EPA sinks and sources methodology, while these values include losses related to transmission and distribution, it ignores upstream emissions from the plants themselves, which the Union of Concerned Scientists includes in analyses such as Reichmuth 2018.

References

Alliance of Automobile Manufacturers (AAM). 2018. Advanced Technology Vehicles Dashboard. Data compiled by the Alliance of Automobile Manufacturers using information provided by IHS Markit. Data last updated November 5, 2018. Online at https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/.

Electric Power Research Institute (EPRI). 2018. Electric Vehicle Driving, Charging, and Load Shape Analysis: A Deep Dive Into Where, When, and How Much Salt River Project (SRP) Electric Vehicle Customers Charge. EPRI, Palo Alto, CA: 2018. 3002013754. Online at www.epri.com/#/pages/summary/000000003002013754/.

Environmental Protection Agency (EPA). 2018. Emissions & Generation Resource Integrated Database (eGRID) 2016, released February 15, 2018. Online at https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid.

Jacobsen, M, and A. van Benthem. 2015. "Vehicle scrappage and gasoline policy," *American Economic Review* 105 (3), 1312-38 (2015). DOI: 10.1257/aer.20130935. Online at www.aeaweb.org/articles?id=10.1257/aer.20130935.

NHTSA (National Highway Traffic Safety Administration). 2006. Vehicle Survivability and Travel Mileage Schedules. DOT HS 809 952. Online at https://permanent.access.gpo.gov/websites/crashstats.nhtsa.dot.gov/pdf/lps98080.pdf.

Reichmuth, D. 2018. "New data show electric vehicles continue to get cleaner." *The Equation* (blog). March 8. Online at https://blog.ucsusa.org/dave-reichmuth/new-data-show-electric-vehicles-continue-to-get-cleaner.

Smart, J., W. Powell, and S. Schey. 2013. "Extended range electric vehicle driving and charging behavior observed early in the EV project," SAE Technical Report 2013-01-1441. DOI: 10.4271/2013-01-1441. Online at https://avt.inl.gov/sites/default/files/pdf/EVProj/2013-01-1441.pdf.

Smart, J., T. Bradley, and S. Salisbury. 2014. "Actual versus estimated utility factor of a large set of privately owned Chevrolet Volts", SAE Technical Report 2014-01-1803. DOI: 10.4271/2014-01-1803. Online at https://avt.inl.gov/sites/default/files/pdf/EVProj/EVProjectUtilityFactorVolt.pdf.

Response: We agree that there are regional differences in the distribution of electric vehicles and the sources of electricity and agree as this increases, this will be important to consider. We have started looking into data sets that would facilitate accounting for these differences within this category but also other end-use sectors for methodological consistency. However, at this time, given the current level of activity and as this is a national inventory, we believe that applying a national average for emissions from charging electric vehicles is appropriate. See also response to comment 4.

Chapter 4. IPPU

4.1 Cement Production

Comment 7: Clarity of cement/clinker production process description in Cement Production Chapter

Specific comments [as page (line number)]:
4-8 (19-31): as in past years, there is an initial impression that calcination is the only thing going on in the kiln and that the kiln is producing cement. It would be clearer to state:

(20) … (CO_2) from both the energy consumed in making the **clinker precursor to** cement and the chemical process itself **to make the clinker**. Emissions from fuels…

(22-26) During the **clinker** production process, **the key reaction (and, apart from preheating to reach calcination temperatures, the major heat-consuming step) is where** calcium carbonate ($CaCO_3$), **in the form of limestone or similar rocks**, is heated in a kiln at a temperature range of about 700 to 1000 degrees Celsius (**about 1,300 to 1,800** degrees Fahrenheit) to form lime (i.e., calcium oxide or CaO) and CO_2 in a process known as calcination or calcining. The quantity of CO_2 emitted during **clinker** production is directly proportional to the CaO content of the clinker. During calcination, each mole of **$CaCO_3$** heated forms one mole of **CaO** and one mole of **CO_2**. **The CO_2 is vented to the atmosphere as part of the kiln line exhaust**.

Comment: Emphasis has been given to clinker (not cement). We should not equate limestone and $CaCO_3$, as many limestones used to make clinker are not especially high purity (in contrast to the lime industry, which does require very high purity limestone). I rounded the degrees F (and can't you just use °C, °F for brevity?) because the °C were rounded. I prefer "CaO" to "lime" as the latter is a vague term (do we mean free-lime content; the product lime; and which type of lime…?)—a better chemical term for CaO would be "calcia".

(28-31) Next, **over a temperature range of 1000 to 1450°C, the CaO combines with alumina, iron oxide, and silica, that are also present in the clinker raw material mix to form hydraulically reactive compounds within white-hot semifused (sintered) nodules of clinker**. **Because one of these "sintering" reactions is highly exothermic, very little extra heat energy is required, and these sintering reactions have essentially no associated process emissions of CO_2.** The clinker is then rapidly cooled to maintain quality, and then **very finely interground** with a small amount of gypsum and potentially other materials (e.g., **ground granulated blast furnace** slag, etc…) to make portland **and similar cements**.

Comment: It is important to stress that, although the clinker is taken to 1450°C, the process emissions of CO_2 (and the vast bulk of the fuel combustion emissions of CO_2) stem from preheating and calcination, NOT from the subsequent sintering reactions to form clinker.

(35-37): I am not sure which USGS data you used for clinker; in general, reliance should be on the Minerals Yearbook chapters and the monthly data and not the Mineral Commodities Summaries (MCS); the MCSs are written before full-year data are available—sadly, this affected botht eh 2016 and 2017 data in the so-called 2018 MCS. I have appended the most recent available data below from the monthly (D16) and annual (D15) surveys. For 2017, only the monthly data are as yet available and they indicate an approx. 1.3% increase in clinker production in 2017, not the approx. 2% that you stated. It is unclear why you state that “Although trend information is available from the USGS…” when, in fact, clinker production data (NOT mere trend data) are published monthly by the USGS (see table 4 in the monthly reports).

4-9 (1-3) you state (likely referring to an earlier USGS estimate) that the USGS reported 75,800 kilotons (citing EPA 2018…) but the table that I have provided below with updated data has the 2017 output as 76,984 kmt. Your table 4-3 should be updated; however, if you retain your 2017 estimate (merely a repeat of 2016), the 2017 emissions should be rounded (in the kt column)—you cannot justify 5-significant figures!

USGS data: U.S. production of clinker
(Metric tons, includes Puerto
Rico)

		D16	D15	D15 - D16	
Year	EPA (kt)	Monthly	Annual	mt	% D15
2013	69,900	69,892,088	69,900,170	8,082	0.012%
2014	**75,800**	75,044,961	75,011,532	-33,429	-0.045%
2015	**76,700**	76,603,356	76,578,773	-24,583	-0.032%
2016	**75,800**	75,997,022	76,022,179	25,157	0.033%
2017*	**75,800**	76,984,145	NA		

*2017 monthly data as of 10/2018 cycle.
"EPA" data used USGS for 2013 & EPA GHG surveys thereafter.

4-9 (6): “…(2009 emissions **were** approx.. 28% lower…)”

(9) “In 2017, **estimated** emissions from cement production **were about 1% lower than those in 2015.**” Comment: 2017 emissions are estimated; the 2017 emissions didn’t decrease from 2015 levels—they were lower than 2015 levels. You could say that 2016 emissions decreased from 2015. In any case, the USGS clinker data above suggest that the emissions likely increased in 2017 from 2016 levels and likely were slightly higher than those of 2015.

4-9 (23-25): **During clinker production, some of the raw materials, partially reacted raw materials, and clinker enters the kiln line’s exhaust system as dust, here collectively referred to as cement kiln dust (CKD). To the degree that the CKD, like the raw materials, contains carbonate raw materials which then get calcined, there is an associated emission of CO_2. At some plants, essentially all CKD is directly returned (insufflated) to the kiln, becoming part of the raw material feed, or is likewise returned to the kiln after first being removed from the exhaust by an electrostatic precipitator or filtration baghouse. In either case, the returned CKD becomes a raw material, thus forming clinker, and the associated CO_2 emissions are simply a component of those calculated for the clinker overall. At some plants, however, the CKD cannot be returned to the kiln at all because it is chemically unsuitable as a raw material, or chemical issues limit the amount of CKD that can be so reused. Any clinker that cannot be returned to the kiln is either used for other (non-clinker) purposes or is landfilled. The CO_2 emissions associated with this non-returned clinker are thus “lost” to the system in that they are not covered by the clinker emissions factor**. The IPCC recommends….

Comment: as originally stated, the key CKD argument—that the "lost" CKD's emissions are not accounted for in the clinker emissions factor—was not made; instead, it seemed like CKD remaining in the kiln somehow was not being counted, which is incorrect. CKD, by definition, does not "remain" in the kiln, but it can be returned to the kiln (becoming part of the raw material feed). Only the CKD that is not returned to the kiln is of interest with respect to "lost" (unaccounted for) emissions. The 2% addition pertains to the likelihood of there being some "lost" CKD.

Table 4-4: apart from comments below regarding the preferred sourcing of the clinker data, it appears that the 2014-2017 data are all rounded (2013 is actually not rounded—except to the nearest 1,000 tons) and while this is ok, such rounding would call for similar rounding in table 4-3.

4-10 (12): Unclear if by "CKD loss can range from 1.5 – 8%" you mean the CKD itself, or the CO_2 emissions associated with CKD "lost" to the system (i.e., not returned to the kiln).

(16): "….the outer 0.2 **inch** of the **total thickness**." A thickness effect, not a surface area effect; carbonation favors high surface area applications—a stucco may carbonate fairly thoroughly & quickly, a thick concrete slab likely will not.

(28-32) Yes, there is a difference between the USGS and EPA data—I would trust the USGS data on clinker production.

Response: EPA appreciates the expert review comments received to help clarify and provide a more accurate description of the cement and clinker production process. The EPA has also performed outreach with the commenter to better understand the comments received. As a result, the Final Inventory report includes an updated description to better reflect the production process per the comments received.

Comment 8: Datasets and data comparison of Clinker Production data

4-9 (34-37) and 4-10 (1-6). You have used the USGS data (I presume from the Minerals Yearbook) for 1990-2013, as you should. It remains unclear why the EPA has switched to its own clinker data thereafter. In discussing data quality, it should be made clear that the USGS has surveyed clinker production data both annually (USBM 1925-1994; USGS thereafter) and monthly (starting 1/1998). For both the monthly and annual surveys, the clinker production data are collected to the nearest ton and are so published in the monthly data; the annual data are presented in units of thousand tons for brevity. The data are rigorously checked: Beginning with the 1998 data, all individual plants' monthly data have been compared with the plants' subsequent annual reporting. Where an annual difference (monthly vs. annual surveys) of 5,000 short tons or more is evident for an individual plant, the plant is queried to resolve the discrepancy (usually resulting in the revisions of some monthly data). For most plants (85%+), the two surveys match exactly for the year or differ by just a few single tons—representing a rounding error from various short to metric ton (or vice versa) conversions. In a few other cases, differences will amount to a few hundred or a few thousand tons but be below the resolution threshold. Fewer than 5% of the forms will have discrepancies of 5,000 short tons or more; these differences get resolved. If the error was indeed with monthly data, the relevant month(s) will be corrected ASAP as revisions in a subsequent monthly report. Of course, this checking is, really, a check on consistency. However, the USGS also collects data on the consumption of raw materials for clinker production vs. those (i.e., additions into the finish mill) for finished cement production. The raw material for clinker data are ratioed to the clinker production as a further check on the data quality or to detect major shifts in “recipes”. Likewise, we collect fuel (energy) data and ratio these to the clinker production to see if things look reasonable.

In the table submitted above, the USGS monthly data for the years shown can be compared with what was published in the USGS annual cement chapters—the agreements are extremely close (in part courtesy of the resolution process!); for the years shown, the two USGS surveys differ by a mere 0.045% (2014) or even less. The data represent 100% reporting of clinker production and are reliable. It is unlikely that the EPA-collected data can match the quality and quality checking of the USGS clinker data—the EPA data are from a single survey only, so it is likely that only the most egregious reporting errors will be evident to the EPA analysts. Do not be surprised if some of the “reasonable” production data reported are really clinker consumption data for the year. Also, do not be surprised if there are short-ton vs. metric ton issues—most U.S. cement plants are owned by foreign companies and some of these do their (U.S.-based) internal accounting in metric tons. It is common for plants to report metric tons when they are supposed to be reporting short tons; inadequate attention is paid by some respondents to the requested reporting units. Anyway, the table above also shows the EPA data for 2014-2017; I view the EPA data as less reliable than the USGS data. By the EPA’s admission, the EPA does not have complete data for 2017—why not then at least use the USGS data for 2017 (albeit that only the monthly data are as yet available) instead of simply repeating the EPA 2016 number?

Response: EPA appreciates the expert review comments received regarding the clinker production data utilized in the estimation of cement production process for the Inventory. The Final Inventory report reflects updated data for 2017 based on EPA’s GHGRP data, as well as an updated comparison of this data with clinker production values reported by the USGS. At the time of the IPPU expert review period, 2017 GHGRP data was not yet available as this data follows the GHGRP data production cycle. EPA conducted outreach with the commenter to discuss available data, differences in data sets including where errors may occur, and provided additional information regarding the EPA’s GHGRP data and verification processes: https://www.epa.gov/sites/production/files/2017-12/documents/ghgrp_verification_factsheet.pdf. EPA was unable to provide additional comparison to the Cement Production chapter between GHGRP data and the various reports published by the USGS due to the timing of Final Inventory publication but will include this information in the QA/QC and Verification section in the April 2020 Inventory submission.

Chapter 5. Agriculture

Comment 9: Clarity and Transparency of the Agriculture Chapter

In general, the methodology and explanation of emissions is clear and appropriate. The analysis is rigorous and comprehensive. In some cases, there is room for improvement (most of which EPA also recognizes):

- The exact source of activity data could be clearer. For example, noting in the text, in a table, or a footnote which survey was used to obtain the data for specific livestock types may be helpful.
- Similarly, including tables depicting changes in activity data overtime would help readers better understand the rationale behind emissions changes.
- Diet characteristics for dairy cattle and some WMS activity data are outdated—recognizing that there are planned improvements in this area.
- The maximum methane generating capacity factor (B_0) is based on ~40 year old research and should be revisited—recognizing there are planned improvements in this area.

Response: EPA appreciates the comment received regarding potential improvements to the overall Agriculture Chapter of the Inventory. EPA notes that many of these improvements are currently reflected in the Planned Improvements sections of the Agriculture Chapter source categories. The EPA plans to consider making changes that would present additional information regarding data sources, as well as changes in data. In the Final Inventory report, Annex 3b does include tables which reference sources of data. For example, Table A-171 provides the source of DE values and Table A-185 provides sources of waste characteristics data for manure management. Additional detail on the specific sources of data for each animal population can be found in the methodology text descriptions within Annex 3b: https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-annex-3-additional-source-or-sink-categories-part-b.pdf. EPA will assess further updates to the text for future reports.

Comment 10: Clarity and Transparency of the Agriculture Chapter
Generally, it appears to be done well with consideration of the intake of digestible energy driving GHG production, as is the most reliable variable. I did wonder about what changes in feed ingredients caused the recent increase in beef cattle methane emissions. The impact of the ethanol industry on the emissions from cattle should be considered. The major byproduct of ethanol production is distillers grains which are fed to beef cattle. I believe these grains may decrease emissions from cattle for a given level of digestible energy. If there is any effect, it might be considered as an aspect of the impact of ethanol-distillers grain production.

Response: EPA appreciates the commenter's support on clarity and transparency of the chapter in describing GHG emissions from enteric fermentation. The underlying diet characterization data used in the Cattle Enteric Fermentation Model (CEFM) to calculate enteric fermentation emissions have not been updated for several years due to prioritization of resources and lack of available data. The recent increases seen in enteric fermentation emissions are resulting from changes to the animal population data, which are updated annually. As resources allow, EPA is working to incorporate updated diet characterization data into the CEFM as noted in the Planned Improvements section of Chapter 5.1; these updated data when incorporated should reflect the use of distillers' grains.

5.1 Enteric Fermentation

Comment 111: Typo on pg. 5-3
P 5-3 line 1. Typo. Should read "but increased from 2015 to 2017"

Response: The description of the Enteric Fermentation chapter has been updated for the Final Inventory publication.

5.2 Manure Management

Comment 12: Adding detail on cattle and swine populations
Page 5-11, line 1. Could give more detail on how often cattle and swine populations are updated (see annex page A-25). Also, swine is not mentioned in this paragraph. Should be included.

Response: EPA notes that information on annual animal populations, including swine, are obtained from the USDA-NASS. Additional detail on methodology for Manure Management is included in Annex 3.11.

Comment 13: Clarity change on pg. 5-8
1. page 5-8, line 4. For clarity, change "produce little or no CH_4" to "produce CO_2 and little or no CH_4"

Response: EPA agrees with this suggested edit and has reflected this change in the Final Inventory report.

Comment 14: Unclear phrase on pg. 5-8
2. page 5-8, line 8. It is unclear what the following phrase refers to: including the animal's digestive system

Response: EPA agrees with this suggested edit and has incorporated changes to make the discussion clearer in the Final Inventory report.

Comment 15: Remove the word 'organic' on pg. 5.8
3. page 5-8, line 13. Remove the word 'organic', organic nitrogen is not denitrified

Response: EPA agrees with this suggested edit and has reflected this change in the Final Inventory report.

Comment 16: Grammar error on pg. 5-8
4. page 5-8, lines 17-18. These clauses are not parallel. For clarity, change the first instance of 'to' to 'into', and change the next two instances of 'in' to 'into"

Response: EPA agrees with this suggested edit and has reflected this change in the Final Inventory report.

Comment 17: Categorization of manure on pg. 5-8
5. page 5-8, line 19. Manure includes urine, either remove urine here or change manure to fecal matter

Response: EPA notes that not everyone assumes that manure includes urine, so this differentiation has been made in the past to clarify this point. However, EPA agrees that this description could be made clearer and has incorporated changes in the Final Inventory report.

Comment 18: Factual error on pg. 5-8
6. page 5-8, line 21. This is factually wrong, organic N is not converted to N_2O. Organic N is first mineralized or decomposed to NH_4 which is then nitrified to NO_3 (producing some N_2O as a byproduct), and the nitrate is then in turn denitrified to N_2O and N_2. NOx can also be produced during denitrification.

Response: EPA appreciates the comment received regarding updates to clarify the text description of manure management emissions within the Agriculture Chapter of the Inventory. The text description at the time of the expert review draft explains the aerobic and then anaerobic conditions that must exist for manure N to process through the N cycle. EPA agrees that this point could be reworded, also to reflect expert review comment, and has incorporated changes into the Final Inventory report.

Comment 19: Better reference on pg. 5-8

7. page 5-8, line 24. A better reference for this is:
Robertson, G. P. and P. M. Groffman. 2015. Nitrogen transformations. Pages 421-446 in E. A. Paul, editor. Soil Microbiology, Ecology, and Biochemistry. Academic Press, Burlington, Massachusetts, USA.

Response: EPA agrees with this suggested edit and has reflected this change in the Final Inventory report.

Chapter 7. Waste

Comment 20: Clarity and Transparency of the Waste Chapter

Comments specifically regarding EPA request for reviewers: "Please provide your overall impressions of the clarity and transparency of the Waste chapter. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Waste chapter."

First, the cited literature accompanying the updated methodology was brief, outdated and extremely disappointing with an emphasis on old literature and outdated concepts. There are literally dozens of articles in the refereed literature during the last two decades which were not cited and, thus, apparently not considered. See, for example, the literature cited in NASEM (2018), Scheutz et al. (2009), and Spokas et al., (2011, 2015). Especially, this literature includes: a) discrete field campaigns quantifying landfill methane emissions [field measurements + statistical analysis], as well as b) advances in field-validated process-based modeling for improved quantification of site-specific landfill methane emissions inclusive of site-specific climate. Moreover, in addition to the paucity of recent refereed literature, the current document under review lists a number of internal contractor memos without apparent online availability via EPA—this strategy (internal discussions without linkage to refereed literature) lacks transparency and is disappointing from such a reputable agency as EPA with historically strong internal technical expertise. Thus it would be helpful if EPA professionals would 1) take advantage of their extensive in-house technical expertise while also overseeing contractor tasks; 2) improve the credibility of methodological analysis via consultation of appropriate refereed literature; 3) more closely collaborate with international colleagues via the IPCC Taskforce for National GHG Inventory Methodologies to insure that U.S. landfill methane emissions are realistically quantified and reported to the UNFCCC; and 4) collaboratively improve, expand, and unify efforts under their own GHGRP and GHGI with other Federal agencies (NASA, NOAA, DOE) to work toward providing the necessary "landfill methane" input for an annually-updated gridded U.S. inventory for anthropogenic methane emissions.

This goal (item #4)—namely, a gridded U.S. inventory—is a major recommendation from a new National Academies of Science, Engineering, and Medicine (NASEM) consensus report on "Improving Inventories for Anthropogenic Methane Emissions in the U.S." (NASEM, 2018). Methane emissions are "complicated" with many anthropogenic and natural sources having spatial and temporal variability spanning orders of magnitude. Certainly, all four of the National Academies' (NASEM, 2018) major recommendations (NASEM, 2018) deserve consideration, encouragement and collaborative implementation by EPA, NASA, NOAA, and DOE—those recommendations are:

1) Continue and enhance current atmospheric methane observations and advance models and assimilation techniques used by top-down approaches.

2) Establish and maintain a fine-scale, spatially and temporally explicit (e.g., gridded) inventory of U.S. anthropogenic methane emissions that is testable using atmospheric observations, and update it on a regular basis.
3) Promote a sustainable process for incorporating the latest science into the GHGI, and regularly review U.S. methane inventory methodologies [see landfill methane-related discussion].
4) Establish and maintain a nationwide research effort to improve accuracy, reliability, and applicability of anthropogenic methane emissions estimates.

Finally, it must be recognized that there are fundamental problems with the current methodology for landfill methane emissions. Use of the IPCC (2006) first order model methodology results in a fundamental dependence for emissions on WIP with the largest sites (largest WIP) having the highest emissions. This is simply not true: literature during the last 2 decades refutes this dependency: rather, emissions are directly related to a) site operational factors (i.e., thickness and composition of site-specific cover materials, presence and operation of engineered biogas recovery) and 2) site-specific climate (affecting temporal variability in emissions over an annual cycle in site-specific soils). [Spokas et al., 2015, 2011; Scheutz et al., 2009] Certainly, temporal soil moisture and temperature changes drive temporal variability in gaseous transport and methanotrophic oxidation rates in individual cover soils. Therefore, credible inventory methods for landfill methane emissions must incorporate consideration of these site-specific operational factors and climate.

However, the current IPCC (2006) methodology assigns a k value for methane generation based on climate but excludes any rigorous consideration of site-specific climate effects on emissions. In contrast, it can be shown via published metadata analysis that, perhaps surprisingly, methane [generation + recovery] from highly-engineered U.S. landfills (i.e., California) is relatively constant across 129 [California] sites irregardless of climate and age of waste (approx. 125 Nm^3 CH_4 per hour per million Mg WIP) [Spokas et al., 2015]. Since much of the further details of this discussion rely on previously published literature, I have attached a relatively large .pdf file [Bogner Nov18 landfill methane GHGI methodology review FINAL.pdf] with more detailed graphs of field data, modeling outcomes, and discussion of:

- the shortcomings of the current methodology;
- one example of a process-based, freely-available model [CALMIM] with independent international field validation for site-specific landfill methane emissions estimates and an example of an inventory application [California landfills, 2010 inventory];
- published comparisons of measured emissions to CALMIM estimates;
- suggestions for advanced CALMIM implementation for site-specific research and engineering strategies to mitigate emissions, and
- bibliography/references cited [NOTE: This bibliography also includes the landfill references cited in these comments—see last 2 pages in pdf file].

Briefly, as discussed above, we now know that there are many fundamental problems with the IPCC (2006) methodology as the basis for inventory reporting for landfill methane—realistically, method abandonment should be a strong consideration based on current science unavailable in 1990's when this methodology was first developed (IPCC, 1996). Instead, an inventory methodology for methane emissions should directly model/estimate emissions based on the known drivers for emissions. Recognizing that EPA must also address backcasting to a 1990 benchmark, I realize that these recommendations for GHGI and GHGRP reporting represent a radical departure from the status quo. However, based on extensive literature during the last 20+ years, and recognizing that the method is largely based on 40-year old science (first order modeling for landfill biogas generation) and a 20+-year old understanding of emissions prior to a critical mass of field data on measured emissions, there should be serious consideration of an alternative methodology. It is also important to point out that the additional methodological complexity added to the GHGRP protocols over historic GHGI methods is not scientifically astute and was never field-validated; rather, the current range of "assigned" emission and oxidation factors for the GHGRP, which are scaled very loosely to ranges of values taken from literature only add complexity without reducing uncertainties or adding any additional value. (For example, on p. 10, it is stated that "There is less uncertainty in the GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used.") Certainly, facility-specific data are needed—however, it is important to incorporate the measurable site-specific parameters which impact directly on site-specific emissions: i.e., areal extent of various cover materials; thickness and composition of each cover material; physical extent of engineered biogas extraction under each cover material [i.e., % of cover area or WIP in each cell]; and, finally, average or annual site-specific climate data (daily pcp, daily min/max temperature). The current "assigned" emission, oxidation, and climate factors incorporated in the GHGRP protocols do not have direct linkage to the site-specific drivers for emissions as discussed above.

I would respectfully suggest that EPA: (1) for each year of the GHGRP annual reports to date, plot site-specific measured methane recovery (Mg methane) vs. measured WIP (Mg waste); and (2) separately plot each of the various HH- "emission" values (Mg CH_4) vs. measured WIP (Mg). Please compare those plots with the plots in the first slides of the attached .pdf file. With regard to 1), this is likely to be a nominally linear relationship with scatter that can be largely attributed to a "known unknown", namely the % of WIP which has installed biogas recovery. This conclusion is based on a parallel plot using 2010 data for California only [also shown in the attached] where it was independently determined by CalRecycle that >90% of the WIP in place in California landfills was "welled" and this plot using California data alone yielded a robust linear relationship (see also Spokas et al., 2015: approx. 125 Nm^3 /hr measured methane recovery per million Mg WIP). With regard to 2), when I did this using averaged 2010- 2014 GHGRP data for 201 sites for 2010-2014, there were no obvious relationships and wide scatter for all the plots using the various HH-values—not promising for the current GHGRP method where the scaling factors were never independently field-validated. As discussed extensively in historic documentation for IPCC (1996, 2006) and the U.S. GHGI and GHGRP, the discussion in previous paragraphs above, as well as in the attached .pdf, the current FOD methodology in its classic application results in estimated emissions that are directly related to measured WIP. As discussed in more detail in the attached .pdf, this is not true and skews site-specific emissions with regard to this misleading assumption [especially note the differences between site-specific emissions for California landfills using IPCC (2006) and the CALMIM model, Spokas et al., 2015]. In contrast (Spokas et al., 2015 and attached .pdf), a revised 2010 site-specific California landfill methane emissions inventory, demonstrated a strong dependency for emissions on cover soils (>90% of emissions from large areas of thinner intermediate cover soils in California) and climate (MAP, MAT: i.e., lower emissions from sites with >500 mm MAP due to increased oxidation rates).

Finally, when using the IPCC (2006) FOD model as a basis for estimated emissions, there is no mechanism for quantitatively crediting the effect of known mitigation strategies on site-specific emissions (i.e., greater density of biogas recovery wells, thicker cover materials w/ alternative physical characteristics, leaving a thin intermediate cover in place prior to vertical expansions, i.e., Cambaliza et al., 2017). This remains a major shortcoming of the current method wherein emissions are incorrectly assumed to be directly related to WIP. This also means that, for localized GHG mitigation strategies, there is no linkage between the estimated emissions and the specific strategy employed.

For all these reasons, consideration should be given to alternative methods such as CALMIM. Even with the need to adjust/backcast values to a 1990 baseline, the use of a science-based, internationally field-validated methodology should be strongly considered at this point in time. This becomes especially important if and when the recommendations of NASEM (2018) are implemented, especially regarding the proposed 0.1 X 0.1 deg. gridded inventory for anthropogenic methane emissions for the U.S. At that point, realistic values for individual methane sources really DO matter and are needed to guide mitigation strategies from multiple localized sources to further reduce emissions.

Response: Regarding recent scientific studies relevant to these estimates, a key part of the QA/QC and verification process for generating the estimates is conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies. To maintain transparency, references cited in the Inventory are those used in the Inventory. A broader range of studies is reviewed and considered. EPA has posted the memos to which the commenter is referring on the same site at which the final Inventory report was posted (now posted under Waste Chapter of current Inventory). However, the commenter is correct that we did not distribute these memos, nor post them, with the expert review draft. In future Inventory preparation cycles we will be more transparent by either including such memos with the expert review distribution or indicate where they may be readily found online for additional technical context.

Regarding gridding CH_4 estimates in the GHG Inventory, in 2016, to improve the ability to compare the national-level inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1° x 0.1° spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization. The gridded methane inventory is designed to be consistent with the 2016 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014 estimates for the year 2012, which presents national totals. Please see https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions. An update to the gridding, using the latest GHG Inventory is in progress.

Regarding the methodology used for the Inventory, please note that the IPCC Guidelines and the FOD model with country specific DOC and k values is used for years 1990-2004 as no directly reported facility specific data is available for those years. We agree with the limitations of the FOD model. Data submitted to the GHGRP is used beginning in 2005 (data submitted for 2010 – 2017 are backcasted to 2005). While landfills without gas collection that report to the GHGRP do use the FOD as the source of their methane generation and emissions, landfill with gas collection also provide actual measurements of landfill gas flow and methane concentration.

We have reviewed CALMIM and other methods and approaches in the past and at the time our assessment was that the current method is the most appropriate, though we will again review CALMIMM and continue reviewing new data for potential future updates. If resources allow, we will also compare the GHGRP data to the 125 Nm3 CH_4/hr/MT WIP value that the commenter describes.

Comment 21: Improving the Waste Chapter

Provide overall impressions of the clarity and transparency of the Waste chapter.

Generally the chapter is clearly written. While there are numerous areas of potential improvement to keep the chapter in line with current scientific findings, such challenges are noted elsewhere. However, the 2nd paragraph on p. 7-2 that opens the chapter states “After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down…”. While this statement is true, greater transparency could be achieved by including information related to the relative time frame that the waste is under aerobic versus anaerobic conditions. As written, a reader unfamiliar with landfills could interpret this statement to mean that landfills function aerobically for substantial periods of time, which is not the case. If the initial description could refer to the fact that aerobic conditions subsist over very short durations, this would be more transparent.

Response: EPA appreciates the commenters feedback regarding transparency. Please note that in a later paragraph on that same page we state, “Methane production typically begins within the first year after the waste is disposed of in a landfill.” This addresses the short duration during which aerobic conditions exist after which time anaerobic bacteria begin to break down the waste. Having said that we agree that include similar text in the 2nd paragraph would increase transparency. We will include such text in the subsequent Inventory report (i.e. April 2020).

7.1 Landfills

Comment 22: Paper Recycling Figure

p. 16 Fig. 7.3. Figure shows almost 80% paper recycling in 2015... That seems unrealistically high even with the (now much diminished) shipping of paper discards to China in that year—please discuss data sources, including international shipping to China and other countries in Asia, and provide further explanation. More specifically, could your “total” for paper discards that year be too low, so that the % of recycled paper [including known tonnage from international shipping/trading] might be correspondingly too high…

Response: The source for the data used in this figure is EPA’s Sustainable Materials Management Facts and Figures Report 2015, which may be found at: https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf; specifically, the amount of food scraps and yard trimmings recycled and composted, and the amount of paper and paperboard recycled and composted are located in Table 25 (yard trimmings and food scraps are under ‘other waste’, paper and paperboard were simply the total % for that category). The methodology document for this report does note that in terms of MSW generation, production data are adjusted by imports and exports from the U.S. where necessary (page 2, paragraph 4 https://www.epa.gov/sites/production/files/2015-09/documents/06numbers.pdf), however, it does not go into specifics as to which source categories these adjustments are made for, therefore it is difficult to discern whether it accounts for shipments to China.

Comment 23: Degradable Organic Carbon (DOC)

A comprehensive Internet search by state was conducted to identify waste characterization studies published as of July 2018. We plan to conduct analyses to generate DOC values specific to the time frame of 1990 to 2004. This time frame is specified because the Inventory uses directly reported GHGRP net emissions, which incorporate the DOC values allowed under the rule, in years beyond 2004. Please *comment and provide information on any additional studies that have not been published on the Internet from 1990 to date that may further these efforts.*

For a lot of reasons, this is not a productive use of EPA's resources. First, there are major issues with the current IPCC (2006) FOD model methodology as discussed above. It is highly unrealistic to expect that a few updated "DOC values" can have any field credibility across the many U.S. sites. In general, such data may be appropriate for and add value to site-specific LCA's with site-specific interpretations, but it is inappropriate for broader state or national applications. Importantly, in Spokas et al., (2015) and also discussed in NASEM (2018) and the attached .pdf, it can be shown that, using 2010 data (NOT modeling) for the 129 full-scale California landfills with biogas recovery, there is a robust linear relationship (r^2 =0.82-0.90 depending on inclusion of the very large Puente Hills site) between site-specific measured annual average methane recovery rate and the measured Waste in Place (WIP). That measured field rate (126 Nm^3 /hr methane recovered per million Mg WIP) implies steady state methane generation without any assumed first order kinetic relationship as traditionally based on the estimated degradable organic carbon content of the waste. The broader implication, of course, is that methane generation in landfills can proceed at "relatively" steady rates over many decades, since the California sites include a wide variety of ages, status (open/closed many years ago), climate regions, and site-specific practices where, unlike for emissions, [generation + recovery] appears to proceed at a quantifiable rate. It is ironic, perhaps, that recent field data have indicated that simpler perceptions of obtainable methane recovery from landfilled waste are valid, whereas our understanding of climatic and site-operational drivers for residual methane emissions have only gotten more complex.

Response: EPA appreciates the commenter's feedback on the usefulness of examining waste characterization studies. As EPA begins preparation of future Inventory emissions estimates, and depending on resources, we will consider this feedback as we investigate any changes to our methodology.

Comment 24: Decay Rate Values

An analysis is being conducted on decay rate values reported by developed countries (e.g. UNFCCC Annex 1 countries) in their annual National Inventory Reports, as well as decay rate values used as defaults in first order decay models, as compared to the U.S. Greenhouse Gas Inventory defaults used in the U.S. Waste model. This analysis is specific to the 1990 to 2004 time frame, because the Inventory uses directly reported GHGRP net emissions, which incorporate the decay rate values allowed under the rule, for years beyond 2004. Please comment and provide information on any additional studies and models that have not been published on the Internet from 1990 to date if any stakeholders have this information available to share.

What is meant by "directly reported GHGRP net emissions"? As there are several HH- values within the GHGRP protocols —which one of the several HH- values is used? It is also a misnomer to infer that these "reported" emissions have any relationship except by serendipity, to actual field-measured emissions at U.S. landfills. As in the previous question, this is not a productive use of EPA resources. Metadata analysis showing a relatively consistent rate of biogas recovery per unit mass of landfilled WIP (see attached .pdf) refutes the use of the FOD model where biogas production rate peaks in the year of disposal and declines exponentially thereafter.

To conclude, I would recommend consultation of:

NASEM (National Academies of Science, Engineering, and Medicine), 2018, Improving Characterization of Anthropogenic Methane Emissions in the United States, Washington, DC: The National Academies Press.doi:https://doi.org/10.17226/24987.

As well as the following literature:
Abichou, T., J. Clark, S. Tan, J. Chanton, G. Hater, R. Green, D. Goldsmith, M. A. Barlaz, and N. Swan. 2010. Uncertainties Associated with the Use of Optical Remote Sensing Technique to Estimate Surface Emissions in Landfill Applications. Journal of the Air & Waste Management Association 60(4):460-470. DOI: 10.3155/1047-3289.60.4.460.

Bogner, J., K. Spokas, and M. Corcoran. 2014. International field validation of CALMIM: A site-specific process-based model for landfill methane (CH_4) emissions inclusive of seasonal CH_4 oxidation. Raleigh: EREF. Available at https://erefdn.org/wp-content/uploads/2015/12/IPCC_Final_Report.pdf, accessed July 24, 2017.

Bogner, J. E., K. A. Spokas, and R. P. Chanton. 2011. Seasonal greenhouse gas emissions (methane, carbon dioxide, nitrous oxide) from engineered landfills: Daily, intermediate, and final California cover soils. Journal of Environmental Quality 40(3):1010-1020. DOI: 10.2134/jeq2010.0407.

Cambaliza, M. O., J. Bogner, G. R., P. B. Shepson, T. A. Harvey, K. A. Spokas, B. H. Stirm, and M. Corcoran. 2017. Field measurements and modeling to resolve m^2 to km^2 CH_4 emissions for a complex urban source: An Indiana landfill study. Elementa--Science of the Anthropocene 5(36). DOI: http://org/10.1525/elementa.145.

Cambaliza, M. O. L., P. B. Shepson, J. Bogner, D. R. Caulton, B. Stirm, C. Sweeney, S. A. Montzka, K. R. Gurney, K. Spokas, O. E. Salmon, T. N. Lavoie, A. Hendricks, K. Mays, J. Turnbull, B. R. Miller, T. Lauvaux, K. Davis, A. Karion, B. Moser, C. Miller, C. Obermeyer, J. Whetstone, K. Prasad, N. Miles, and S. Richardson. 2015. Quantification and source apportionment of the methane emission flux from the city of Indianapolis. Elementa: Science of the Anthropocene 3(37). DOI: 10.12952/journal.elementa.000037.

Chanton, J., and K. Liptay. 2000. Seasonal variation in methane oxidation in a landfill cover soil as determined by an in situ stable isotope technique. Global Biogeochemical Cycles 14(1):51-60. DOI: 10.1029/1999gb900087. Chanton, J., T. Abichou, C. Langford, G. Hater, R. Green, D. Goldsmith, and N. Swan. 2011. Landfill Methane Oxidation Across Climate Types in the U.S. Environmental Science & Technology 45(1):313-319. DOI: 10.1021/es101915r.

Chanton, J., T. Abichou, C. Langford, G. Hater, R. Green, D. Goldsmith, and N. Swan. 2011. Landfill Methane Oxidation Across Climate Types in the U.S. Environmental Science & Technology 45(1):313-319. DOI: 10.1021/es101915r.

Chanton, J. R., D. K. Powelson, and R. B. Green. 2009. Methane oxidation in landfill cover soils, is a 10% default value reasonable? Journal of Environmental Quality 38(2):654-663. DOI: 10.2134/jeq2008.0221.

de la Cruz, F. B., R. B. Green, G. R. Hater, J. P. Chanton, E. D. Thoma, T. A. Harvey, and M. A. Barlaz. 2016. Comparison of Field Measurements to Methane Emissions Models at a New Landfill. Environmental Science & Technology 50(17):9432-9441. DOI: 10.1021/acs.est.6b00415.

Foster-Wittig, T. A., E. D. Thoma, R. B. Green, G. R. Hater, N. D. Swan, and J. P. Chanton. 2015. Development of a mobile tracer correlation method for assessment of air emissions from landfills and other area sources. Atmospheric Environment 102:323-330. DOI: 10.1016/j.atmosenv.2014.12.008.

Goldsmith, C. D., J. Chanton, T. Abichou, N. Swan, R. Green, and G. Hater. 2012. Methane emissions from 20 landfills across the United States using vertical radial plume mapping. Journal of the Air & Waste Management Association 62(2):183-197. DOI: 10.1080/10473289.2011.639480.

Liptay, K., J. Chanton, P. Czepiel, and B. Mosher. 1998. Use of stable isotopes to determine methane oxidation in landfill cover soils. Journal of Geophysical Research Atmospheres 103(D7):8243-8250. DOI: 10.1029/97jd02630

Maasakkers, J. D., D. J. Jacob, M. P. Sulprizio, A. J. Turner, M. Weitz, T. Wirth, C. Hight, M. DeFigueiredo, M. Desai, R. Schmeltz, L. Hockstad, A. A. Bloom, K. W. Bowman, S. Jeong, and M. L. Fischer. 2016. Gridded National Inventory of US Methane Emissions. Environmental Science & Technology 50(23):13123-13133. DOI: 10.1021/acs.est.6b02878.

Miller, S. M., S. C. Wofsy, A. M. Michalak, E. A. Kort, A. E. Andrews, S. C. Biraud, E. J. Dlugokencky, J. Eluszkiewicz, M. L. Fischer, G. Janssens-Maenhout, B. R. Miller, J. B. Miller, S. A. Montzka, T. Nehrkorn, and C. Sweeney. 2013. Anthropogenic emissions of methane in the United States. Proceedings of the National Academy of Sciences of the United States of America 110(50):20018-20022. DOI: 10.1073/pnas.1314392110.

Scheutz, C., J. Samuelsson, A. M. Fredenslund, and P. Kjeldsen. 2011. Quantification of multiple methane emission sources at landfills using a double tracer technique. Waste Management 31(5):1009-1017. DOI: 10.1016/j.wasman.2011.01.015.

Scheutz, C., P. Kjeldsen, J. E. Bogner, A. De Visscher, J. Gebert, H. A. Hilger, M. Huber- Humer, and K. Spokas. 2009. Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions. Waste Management & Research 27(5):409-455. DOI: 10.1177/0734242X09339325.

Spokas, K., J. Bogner, and J. Chanton. 2011. A process-based inventory model for landfill CH_4 emissions inclusive of soil microclimate and seasonal methane oxidation. Journal of Geophysical Research--Biogeosciences 116(G4). DOI: 10.1029/2011JG001741. Spokas, K., J. Bogner, M. Corcoran, and S. Walker. 2015. From California dreaming to California data: Challenging historic models for landfill CH_4 emissions. Elementa: Science of the Anthropocene 3(51). DOI: 10.12952/journal.elementa.000051.

Spokas, K., J. Bogner, M. Corcoran, and S. Walker. 2015. From California dreaming to California data: Challenging historic models for landfill CH4 emissions. Elementa: Science of the Anthropocene 3(51). DOI: 10.12952/journal.elementa.000051.

Spokas, K. A., and J. E. Bogner. 2011. Limits and dynamics of methane oxidation in landfill cover soils. Waste Management 31(5):823-832. DOI: 10.1016/j.wasman.2009.12.018.

Streese-Kleeberg, J., I. Rachor, J. Gebert, and R. Stegmann. 2011. Use of gas push-pull tests for the measurement of methane oxidation in different landfill cover soils. Waste Management 31(5):995-1001. DOI: 10.1016/j.wasman.2010.08.026.

Taylor, D. M., F. K. Chow, M. Delkash, and P. T. Imhoff. 2016. Numerical simulations to assess the tracer dilution method for measurement of landfill methane emissions. Waste Management 56:298-309. DOI: 10.1016/j.wasman.2016.06.040.

Response: EPA appreciates the commenter's feedback on the relationship between reported GHGRP data and field measurements. As EPA begins preparation of future Inventory emissions estimates, and depending on resources, we will consider this feedback as we investigate any changes to our methodology. EPA also appreciates the list of literature provided by the commenter.

Comment 25: The Scale-Up Factor for MSW Landfills
Recognizing that the GHGRP does not include every MSW landfill in the country – (MSW landfills that ceased taking waste prior to 1980 or have potential emissions less than 25,000 tons CO_2e) – we continue to support EPA's decision to use a scale-up factor to estimate emissions from non-reporting landfills in the draft 1990-2017 Inventory. As part of the expert review of the draft 2018 Inventory, the landfill sector reviewed the largest of the Agency's list of potential landfills not reporting emissions to the GHGRP. We found that the Agency overestimated Waste in Place (WIP) by more than 60 percent and recommended adjusting the scale-up factor to 5 percent from 12.5 percent. We were pleased that EPA adjusted the factor for the 2018 Inventory and employed a lower scale-up factor of 9 percent; however, **we do recommend that EPA revisit using an even lower factor of five percent in the 2019 Inventory. EPA should evaluate and revise the scale-up factor on a routine basis to account for the additional WIP for sites reporting to GHGRP which is likely to significantly exceed non-reporting facilities that have closed and are no longer receiving waste.** The Agency can reasonably anticipate a downward trend in WIP at landfills outside the GHGRP, and the scale-up factor should reflect these changing landfill demographics.

Response: EPA appreciates commenter's support of the scale-up factor approach to account for landfills that do not report to the GHGRP. EPA also appreciates and agrees with the commenter's feedback that the scale-up factor should be evaluated on a routine basis. EPA plans to reexamine the scale-up factor with each inventory cycle to determine if there are additional landfills reporting to the GHGRP such that the WIP assumed for those landfills can be removed from the scale-up factor. At the same time, EPA will also account for those landfills that have stopped reporting to the program because they were able to exercise the off-ramp provisions.

Comment 26: Methane Oxidation Factor
For the period 1990 – 2004 in the inventory time series, EPA calculates a national estimate of methane generation and emissions using a combination of secondary data sources that detail the annual quantity of waste landfilled and the annual quantity of methane recovered from facilities with landfill gas collection and control systems. EPA applies a 10% oxidation factor to all facilities for the years 1990 to 2004. This ten percent default factor contrasts significantly with the average methane oxidation factor of 19.5 percent applied through use of GHGRP data, to the later years of the time series (2005 to 2016). Importantly, the 19.5 percent average oxidation rate incorporated in the GHGRP, subpart HH emissions data is premised on a more detailed and up-to-date estimation approach than is the default value of 10 percent. It is also a conservative average value, as the GHGRP methodology restricted the maximum oxidation rate to 35 percent.

In its work to review and revise the method for calculating methane oxidation under subpart HH of the GHGRP, EPA acknowledged the need to update the default 10 percent oxidation value. The default value was based on only one field study, at a landfill without gas collection and control, and did not reflect the much higher oxidation values found in numerous subsequent, peer-reviewed field studies. **Given the plethora of scientific studies showing methane oxidation to be several times higher than the EPA and IPCC default value, we strongly recommend EPA apply a revised value (perhaps the average oxidation value from the GHGRP) to the earlier years of the time series.**

Response: EPA appreciates commenter's feedback on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017. As stated in the Planned Improvements section of Section 7.1 of the Inventory, EPA is continuing to review new literature and investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2017) averages to 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.

Comment 27: Degradable Organic Carbon (DOC)

Chapter 7 of the draft inventory explains that EPA uses one DOC value of 0.20 to calculate emissions for the years 1990 through 2004, and uses emissions reported through the GHGRP for years 2005 through 2017. The GHGRP allows landfills to use 0.20 for bulk MSW or allows a landfill to further delineate waste streams by accounting for separate shipments of C&D waste, which uses a DOC of 0.08, and separate shipments of inert wastes, which may use a DOC of 0.0. If a landfill delineates in this way, it must use a DOC of 0.31 for its MSW waste volumes, which applies an artificially high DOC to MSW, and inappropriately overestimates emissions. The required DOC value of 0.31 fails to account for the significant volumes of C&D and inert wastes that are incorporated in MSW, and which cannot be separated from the MSW or accounted for distinctly, as can discrete shipments of inert wastes from industrial or C&D recycling facilities.

While we are pleased to learn that EPA plans to revisit the DOC value of 0.20, we question why the Agency is focusing first on the early years of the inventory rather than the later portion of the time series. We believe that the fundamental shifts in the characterization of waste disposed in landfills has occurred in the later portion of the time series and that the research conducted thus far by state agencies and the Environmental Research and Education Foundation (EREF) are illustrative of those changes. **We strongly recommend that EPA instead focus on the second half of the time series and reevaluate the DOC values incorporated in subpart HH of the GHGRP, which underpins the data used for those years of the inventory.**

In 2016, the Environmental Research and Education Foundation (EREF) undertook a state-based study of DOC values for both landfills receiving only MSW (MSW Only Landfills) and for Non-MSW Material going to MSW Landfills. The DOC guideline recommended by EPA for MSW Only Landfills is 0.31 and the recommended guideline for Non-MSW material going to MSW landfills is 0.20. EREF concluded both of these guidelines over-estimate the amount of organic waste deposited in landfills, which results in inaccurate estimates of landfill gas generation and methane emissions. Furthermore, neither of the EPA-recommended DOC guidelines have been reviewed in many years. We therefore support EPA's view that it is time to update the DOC values and believe that the most valuable focus would be to reassess the DOC values incorporated in the GHGRP used for inventory years 2005 forward.

EREF reviewed recent waste composition studies for MSW Only Landfills conducted by 13 states and confirmed that waste composition has and continues to change over time, as fewer organic materials are sent to MSW landfills. In fact, the EREF results show that the percent of the MSW-only stream that is organic waste ranged from 50.1% to 69.4%, with an average of 60.2% (Table 1).[1] EPA data also indicate that the fraction of organics going to landfills generally declined from the earliest studies through 2013. Since EPA cites the EREF research as a rationale for reassessing DOC values for 1990-2004, the following quotes from EREF clearly suggest that the data strongly suggest reevaluating DOC values used in the GHGRP for years 2005 and later:

> Subsequent analyses were performed using both state characterization study data and EPA Facts and Figures data to compute DOC values for MSW (DOC_{MSW}). An average DOC_{MSW} of 0.184 was computed from the state study data, with values ranging from 0.142 – 0.209. All characterization studies had DOC_{MSW} values significantly less than the default value of 0.31, which suggests this value is not representative of real-world conditions for MSW (Table 2; Figure 4). Analysis of U.S. EPA data … also results in a significantly lower DOC_{MSW} value compared to the U.S. EPA guideline of 0.31, with DOC_{MSW} values ranging from 0.218 in 1994 to a minimum of 0.165 in 2011 (Figure 4; Appendix B). Both the state characterization studies and U.S. EPA Facts and Figures data independently suggest that a DOC guideline value of 0.31 for MSW is not representative of the landfilled MSW stream. …
>
> The use of a single DOC value as a guideline for all U.S. landfills makes the implicit assumption that waste composition does not change over time or due to location. The results presented here suggest these are not valid assumptions and that, collectively, the use of a static DOC value of 0.31 may lead to inaccurate estimates of landfill gas emissions for landfills that only accept MSW. Because this specific analysis is focused only on MSW materials, one would expect the inclusion of non-MSW materials going to a landfill to impact DOC estimates even more.[2]

With respect to Non-MSW going to MSW Landfills, EREF finds "a common assumption is that all waste materials entering MSW landfills consist only of MSW materials. As noted previously, MSW Landfills rarely accept MSW exclusively. Rather, most MSW Landfills (landfills in 45 states) are authorized to accept other Subtitle D wastes in addition to MSW."[3] In addition, EREF notes:

> Given that a third of incoming waste to MSW Landfills consists of non-MSW materials, there is significant potential for non-MSW materials to impact the relative fraction of organics and degradable organic carbon (DOC) of the MSW Landfill waste stream.[4]
>
> The amount and types of non-MSW Subtitle D organic wastes impact the DOC value for the landfilled waste since it consists of both MSW and non-MSW streams. This combined DOC value (DOC_{SubD}) incorporates degradable organic carbon from all Subtitle D wastes accepted at MSW Landfills (both MSW and non-MSW). … State waste characterization studies were used to estimate the relative fraction of each organic constituent for C&D and industrial waste … and DOC for each waste type was calculated using Equation 1b. Based on this analysis the DOC_{SubD} value of landfilled waste is 0.161 (Table 6)."[5]

EREF also highlights that the DOC_{SubD} value:

> … is lower than the guideline value of 0.20 for bulk waste. It is also lower than the average DOC_{MSW} value of 0.184 computed in the prior section, indicating the inclusion of non-MSW decreases overall DOC. Using the same approach as for the DOC_{MSW} analysis, state-specific organics content and DOC_{SubD} values for all fourteen states with sufficient data were determined

> and presented in Table 7, below. … The results, all for 2013, highlight differences in $\mathrm{DOC}_{\mathrm{SubD}}$ based on locale and suggest the use of a static 0.20 guideline for bulk waste may lead to inaccurate estimates of methane generation and emissions, especially in some areas.[6]

Thus, EREF concludes as follows:

> The average computed DOC value for MSW using state data was 0.184, or roughly three-fifths of the MSW guideline value. The average computed DOC value for bulk waste using state data was 0.161, or roughly four-fifths of the bulk waste guideline. This analysis suggests that the U.S. EPA's guideline DOC values of 0.31 for MSW-only landfills and 0.20 for facilities accepting non-MSW Subtitle D wastes overestimate DOC at these landfills and may result in inaccurate estimates of landfill gas generation and methane emissions.[7]

Based on this review of the DOC values for MSW landfills, the waste sector concludes that the long-standing DOC values developed in the past are inaccurate and are likely to over-estimate both landfill gas generation and methane emissions. The data provided by EREF confirms that two trends are driving the changes at MSW Landfills. First, many MSW Landfills are handling less organic matter now, and this trend is anticipated to continue due to state and local organics diversion goals. Second, the increase of Subtitle D non-MSW waste disposed has altered the DOC for all waste deposited in MSW Landfills. EPA validates these trends in the Inventory's Chapter 6 discussion of carbon sequestration of harvested wood products, yard waste and food waste, which shows a significant reduction in sequestered carbon since 1990 due to reduced volumes of organic wastes disposed in landfills.

Based on EREF's research, **we urge EPA to update the DOC values to reflect significant changes in the amounts and types of organic materials being landfilled over recent years.** The values now in use are inaccurate and should not be used going forward. **We recommend that EPA review and update the DOC values for the entire time series for the 2019 version of the GHG Inventory, and as a priority update the DOC values used in calculating GHG emissions under Subpart HH of the GHGRP.**
Further, as EPA clearly recognizes that the composition of the waste at MSW Landfills has changed and continues to change, we suggest the Agency add an additional factor, "(5) the composition of the waste" to the sentence on line 42, page 7-2 of the waste chapter that begins: "Methane generation and emissions from landfills are a function of several factors."

[1] Staley, B.F. and Kantner, D.L., *Estimating Degradable Organic Carbon in MSW Landfills and the Impact of Non-MSW Materials*, EREF – Environmental Research and Education Foundation, 2016, Table 1, p. 4.
[2] Ibid., pp. 6 - 7.
[3] Ibid., p. 8.
[4] Ibid., p. 10.
[5] Ibid., p. 11.
[6] Ibid., p. 12.
[7] Ibid., p. 13.

Response: As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA currently uses one value of 0.20 for the DOC for years 1990 to 2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide).

EPA also notes the recommendation from the commenter regarding the DOC values used in the GHGRP, in the context of new information on the composition of waste disposed in MSW landfills; these newer values could then be reflected in the 2005 and later years of the Inventory. EPA is continuing to investigate publicly available waste characterization studies and calculated DOC values resulting from the study data.

Comment 28: The k Factor (Methane Generation Rate Constant)

On page 7-13 EPA notes that it began investigating using k-values based on climate. The waste sector strongly supports EPA's plans to review these k values against new data and other landfill gas models, as well as assess the uncertainty factor applied to these k values in the Waste Model. We have been concerned that these k-values are outdated and rife with uncertainty, as confirmed by the *Draft AP 42.2.4 Municipal Solid Waste Landfills*, which states:

> There is a significant level of uncertainty in Equation 2 and its recommended default values for k and L_o. The recommended defaults k and L_o for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH_4 emissions that ranged from ~30 to 400% of measured values and had a relative standard deviation of 0.73 (Table 2-2). The default values for wet landfills were based on a more limited set of data and are expected to contain even greater uncertainty.[8]

The waste sector has previously highlighted the significant issues with the k values used in the Draft AP-42 Section 2.4: Municipal Solid Waste Landfills. In fact, EPA has never finalized AP-42 for MSW landfills, despite the k-value issues identified *by EPA* in both AP-42 and the Background Information Document. With uncertainties in CH_4 emissions ranging from -30% to 400% under EPA's assessment of the LandGEM model, it is difficult to rely on these data. For this reason, we support EPA's plan to review and resolve the significant problems in the k value data set.

[8] U.S. EPA, *Draft AP 42.2.4: Municipal Solid Waste Landfills*, October 2008, p. 2.4-6.

Response: As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA began investigating the k values for the three climate types (dry, moderate, and wet) against new data and other landfill gas models, and how they are applied to the percentage of the population assigned to these climate types. EPA will also assess the uncertainty factor applied to these k values in the Waste Model. Like the DOC value, the k values applied through the Waste Model are for the years 1990 to 2004; the k values for 2005 to 2017 are directly incorporated into the net methane emissions reported to EPA's GHGRP. EPA will continue investigating the literature for available k value data to understand if the data warrant revisions to the k values used in the Waste Model between 1990 to 2004.

Comment 29: Industrial Food Processing Waste Datasets

Please comment on datasets that detail the quantities of industrial food processing waste that is disposed of in industrial waste landfills.

The waste sector does not have datasets on food processing waste disposed at industrial waste landfills.

Response: EPA appreciates commenter's feedback on lack of available data on industrial food processing waste.

Comment 30: Waste Characterization Studies

A comprehensive Internet search by state was conducted to identify waste characterization studies published as of July 2018. We plan to conduct analyses to generate DOC values specific to the time frame of 1990 to 2004.

The waste sector shared the list of waste characterization studies evaluated by EPA with EREF to see if the research foundation might have information on additional waste characterization studies. In comments above we also strongly recommended that EPA reevaluate the default DOC values and focus first on the values used in the GHGRP and applied to emissions estimates for 2005-2017.

Response: EPA appreciates commenter's feedback on the availability of additional waste characterization studies and the list of studies provided. EPA notes that review and update of the DOC values are part of the ongoing Planned Improvements outlined in section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks. See responses to comments 27 and 33.

Comment 31: Methane Emissions from Pulp and Paper Landfills

NCASI notes that the revisions to US paper, paperboard, and market pulp production also reduced the estimates of mass of solid waste from pulp and paper facilities entering landfills that would contribute to methane emissions (Table A-1). It is our understanding that this revision in mass loading does not reduce methane emissions from pulp and paper landfills in the inventory because EPA is now using directly reported EPA Greenhouse Gas Reporting Program (GHGRP) information with a scale-up factor to calculate these emissions for the pulp and paper industry. NCASI would appreciate confirmation that this is indeed the approach being used to characterize current methane emissions from pulp and paper landfills.

Response: EPA appreciates commenter's feedback on the contribution of solid waste from pulp and paper facilities to the estimated emissions from industrial waste landfills in the U.S. Inventory of Greenhouse Gas Emissions and Sinks: 1990-2017. However, the commenter appears to misunderstand how emissions from industrial waste landfills are accounted for in the Inventory. The methodology currently uses production values for pulp and paper from the Lockwood-Post Directory (and USDA derived values for food and beverage), not data submitted to the GHGRP. In the Inventory, EPA does discuss recent analysis of data submitted to Subpart TT (Industrial waste landfills) of the GHGRP to determine if production values from other sectors that generate organic waste which could be disposed of in industrial landfills should be included in the Inventory estimates. However, no changes have been made to date as a result of this analysis.

Comment 32: Methane Oxidation from Landfill Cover Soils

The document notes (page 7-9) that the amount of methane oxidized by the landfill cover at MSW landfills was assumed to be 10% of the methane generated that was not recovered from 1990 to 2004. Note that at this point, there have been numerous studies conducted by academic researchers documenting methane oxidation over a variety of cover and climatic conditions that suggest methane oxidation is substantially higher than 10% in most circumstances. While the "Planned Improvements" section notes that the methane oxidation value used between 2005 to 2016 averages at 19.5%, this value appears to be applied across all landfills and is not adjusted based on geospatial differences and cover conditions. Given the substantial body of knowledge on methane oxidation from landfill covers that documents a higher and more variable range of methane oxidation values, consideration should be given to revising the 10% assumption to be more aligned with current scientific findings and values used should more accurately reflect geospatial differences in oxidation values. The studies listed below provide a few examples. Note that a link to the final report for each project can be found at the bottom of the web page. Peer-reviewed articles are also published for most of these projects and can be provided if necessary.

1) Methane Oxidation: Field-scale test sections experiment https://erefdn.org/methane-oxidation-field-scale-test-sections-experiment/

2) International Field Validation of a New IPCC Model for Landfill Methane Emissions https://erefdn.org/international-field-validation-of-a-new-ipcc-model-for-landfill-methane-emissions/

3) Constraining the Effects of Secondary Porosity on CH_4 Oxidation https://erefdn.org/constraining-the-effects-of-secondary-porosity-on-ch4-oxidation/

Response: EPA appreciates commenter's feedback on the oxidation factor as applied to estimating emissions from MSW landfills in Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017. As stated in the Planned Improvements section of Section 7.1 of the Inventory, EPA is continuing to review new literature and investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2017) averages to 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent. EPA further appreciates the source references provided by the commenter.

Comment 33: Degradable Organic Carbon (DOC)
In the "Planned Improvements" section of the chapter (page 7-13), it is noted that for the years from 1990 to 2004, a DOC value of 0.20 is used to calculate emissions. Recent research conducted by EREF using waste characterization studies to compute DOC entering landfills suggest that DOC values have been changing over time and in recent years are lower than the guideline value of 0.20. This appears to be due to an increasing fraction of non-MSW material being placed into MSW landfills, which in some cases, represents a substantial portion of received tonnage. Additionally, another factor attributed to lower DOC values is due to less organics entering landfill compared to prior years. Collectively, these results suggest that the guideline value of 0.20 may overestimate DOC, resulting in subsequent errors in estimated landfill gas emissions. A copy of the report is attached for reference and the "Conclusions" section of the report provides key findings that would be useful for review in EPA's effort to update the DOC values.

However, it should be stressed that the data aggregated in the EREF report suggest that DOC values are changing and, over the past 10-15 years, the DOC is significantly lower than the guideline value. DOC values prior to this time frame were not included in the analysis performed by EREF and data was not analyzed prior to the year 2000. Based on the changing waste composition to landfills over time, DOC values determined should be used to compute emissions that are aligned and within the same time frame. In other words, the data suggest it would not be appropriate to use a DOC value computed from 1990, for example, to estimate emissions for 2015. This is a key consideration when using waste characterization studies to estimate DOC values and apply said values to an emissions inventory.

Response: As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA currently uses one value of 0.20 for the DOC for years 1990 to

2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide). EPA also notes the recommendation from the commenter regarding the DOC values used in the GHGRP, in the context of new information on the composition of waste disposed in MSW landfills; these newer values could then be reflected in the 2005 and later years of the Inventory. EPA is continuing to investigate publicly available waste characterization studies and calculated DOC values resulting from the study data. EPA also appreciates commenters assessment that it is important to consider the timeframe when making changes to the DOC value used in the Inventory calculations. Changes for the later portion of the time series (e.g. 2005-2017) may not be appropriate for the earlier part of the timeseries (e.g. 1990-2005).

Comment 34: Industrial Food Processing Waste Datasets

Please comment on datasets that detail the quantities of industrial food processing waste that is disposed of in industrial waste landfills.

We are not aware of any significant database that exists and the level of effort to ascertain a reasonably accurate estimate would be significant.

Response: EPA appreciates commenter's feedback on lack of available data on industrial food processing waste and agrees that obtaining this data would require significant effort.

Comment 35: Degradable Organic Carbon (DOC)

A comprehensive Internet search by state was conducted to identify waste characterization studies published as of July 2018. We plan to conduct analyses to generate DOC values specific to the time frame of 1990 to 2004. Please provide any additional information on studies from this time frame.

A study performed in 2009 by Staley and Barlaz aggregated a number of robust statewide characterization studies to ascertain variability in waste composition for the purpose of looking at methane yield and carbon sequestration. The paper may provide some insight relative to computing DOC values in the time frame referenced.

Staley, B.F. and M.A. Barlaz (2009). Composition of MSW in the U.S. and Implications for Carbon Sequestration and Methane Yield. Journal of Environmental Engineering, p. 901-909.

Response: EPA appreciated commenter's feedback to the charge question. EPA had reviewed the study reference by the commenter in preparing the U.S. Inventory of Greenhouse Gas Emissions and Sinks: 1990-2017 and will retain this study part of ongoing review of the DOC value per planned improvements. See also responses to comments 27 and 33.

Comment 36: Decay Rate Values

An analysis is being conducted on decay rate values reported by developed countries relative to US GHG Inventory defaults from 1990 to 2004. Please provide any additional information on studies from this time frame.

We are not aware of additional studies that the EPA would not already be aware of.

Response: EPA appreciated the commenter's feedback on the lack of additional studies available on decay rates.

Comment 37: MSW Landfills Emission Calculations
Page 7-3, line 1&2: How was it calculated that MSW landfills accounted for approximately 95% of total landfill emissions and industrial waste landfills accounted for the remainder? (CC)

Response: This percentage was calculated by comparing the U.S. Waste Model results for MSW landfills and industrial landfills when estimating emissions for the 2017 Inventory year.

Comment 38: Operating MSW Landfills Source
EPA/ORCR has an estimate of the number of operating MSW landfills, which is 1738. The source is Advancing Sustainable Materials Management Facts and Figures: 2015 Tables and Figures, Table 34, page 35. This can be inserted on page 7-3, line 2. (HP)

Response: EPA has noted commenter's feedback and has incorporated this information and citation within Section 7.1 of Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks.

Comment 39: MSW Data Source
On page 7-3, line 17, it says 205 MMT MSW was landfilled in 1990; 226 MMT MSW was landfilled in 2000; and 206 MMT MSW was landfilled in 2017. What is the source of this data? (HP)

Response: These quantities are calculated quantities within the solid waste inventory framework for the years listed, they are arrived at by using the U.S. Waste Model which is based on the Waste Model within the 2006 IPCC Guidelines.

Comment 40: Nationwide Municipal Solid Waste Data Sources
Page 7-6, line 20- mentions EREF's MSW management data but not EPA's Facts & Figures? (CB)

Response: EPA appreciates the commenter's feedback and will review this portion of the report to determine if it is appropriate to include EPA's Facts and Figures report.

Comment 41: Nationwide Municipal Solid Waste Data Sources
Page 7-14: The correct title of EPA's report is **Advancing Sustainable Materials Management Facts and Figures report.** We also have the following website to the report if that is of interest: Facts and Figures (SG)

Response: EPA appreciates the commenter's feedback and has made this correction to the title of the EPA report.

Comment 42: Biocycle/SOG reports
The report notes that the Biocycle/SOG reports are no longer published. I would recommend calling Biocycle to see if they still want their publication name included as it been several years since they stopped published the SOG. Also, in the third paragraph, the authors of this paper use the present tense to describe SOG's report (e.g. The SOG surveys, now EREF, collect state-reported data…). This sentence seems to indicate that SOG is still being published. (SG)

Response: EPA appreciates the commenter's input on how Section 7.1 of Chapter 7 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks characterizes the Biocycle/SOG reports. EPA will review the tense used to describe the SOG survey and make any necessary corrections in subsequent Inventory reports.

Comment 43: Adding a Footnote for Advancing Sustainable Materials Management Report
On page 7-16, line 4, Data for years 2012 and 2013 are from EPA's Advancing Sustainable Materials Management: 2014 Tables and Figures Report (Table 4) published in December 2016. This should be added to the footnotes. (HP)

Response: EPA appreciates the commenter's input. Proper citations have been included in the final Inventory report.

Comment 44: Industrial Waste Landfill Estimates
Page 7-3, line 21&22: "The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper, and food processing 21 sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 10.2 MMT in 2017 (see 22 Annex 3.14, Table A-254)." (CC)

- Can we see Annex 3.14, Table A-254. I'm very curious about these estimates and what additional estimates there are on industrial waste. (CC)

Response: Annex 3, which includes Annex 3.14 is posted to EPA's website at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2017

Comment 45: Generation and Disposal Data
Page 7-6, line 16&17: why is the SOG surveys used for generation and disposal data instead of the Facts and figures Report? (CC)

Response: When the SOG survey data was first used for preparation of the emissions estimates for the U.S. Greenhouse Gas Inventory of Emissions and Sinks, the EPA Facts and Figures report was not yet in publication. The SOG survey data are only used for the years 1990-2004 of the Inventory time series, pre-dating the years for which the Facts and Figures values are available. Therefore, SOG data estimates remain the most accurate account of waste generation and disposal for those early years of the Inventory time series.

7.2 Wastewater Treatment

Comment 46: Paper, Paperboard, and Market Pulp Production
Based upon discussions between EPA and NCASI in early 2018 regarding methane emissions from pulp and paper waste water treatment operations, EPA determined that updates to US paper, paperboard, and market pulp production were appropriate, which resulted in changes to the production time series (Table 7-10) and the methane emissions attributed to pulp and paper wastewater treatment facilities (Table 7-9). NCASI has reviewed section 7.2 Wastewater Treatment, finds the results to be in accordance with NCASI calculations, and thanks EPA for implementing the changes.

Response: EPA appreciates the commenter's feedback supporting the changes made to the production time series and the methane emissions attributed to wastewater treatment at pulp and paper facilities.

7.3 Composting

Comment 47: Compost Emission Factor
In ideal conditions, the composting process occurs at a moisture content of between 50 and 60%, but the moisture content of feedstocks received at composting sites varies and can range from 20% to 80%. It is common for moisture to be added to dry feedstocks prior to the start of composting to optimize the biological process. In the calculation of emissions from composting in the draft chapter, it appears that all incoming wastes were assumed to have a moisture content of 60%. If 60% is not reflective of the actual weighted average of all feedstocks, this will introduce errors in the inventory calculation that could be significant.

We recommend that the calculations be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents, or ask that further information be provided on the rationale for assuming 60% as the average moisture content of all inbound materials

Response: EPA notes commenter's feedback on the moisture content levels used in the calculation of emissions from composting. The calculations for composting are based on IPCC Tier 1 methodology defaults. Under this methodology, the emission factors for CH_4 and N_2O assume a moisture content of 60% in the wet waste. (IPCC 2006). EPA has added this detail to the Methodology section of Section 7.3 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017 so that the source of the moisture content is more transparent. In addition, EPA has added to the Planned Improvements section of Section 7.3 that EPA is looking into the possibility of incorporating more specific waste subcategories and category-specific moisture contents into the emissions estimates for composting in the United States to improve accuracy. However, to date the EPA has not been able to locate substantial information on the composition of waste at U.S. composting facilities to do so. As additional data becomes available on the composition of waste at these facilities, EPA will consider using this information to create a more detailed calculation of U.S. composting emissions.

Comment 48: Datasets Available on Industrial Composting Facilities.
Please comment on datasets available on industrial composting facilities.

Currently, to our knowledge no comprehensive database exists for composting facilities. With this said, EREF has an effort currently underway that aims to develop a reasonably complete facility list for composting facilities. However, the project is moving slowly and it will likely be 2020 before this list is available.

Response: EPA appreciates commenter's feedback on the current lack of a comprehensive database of composting facilities. EPA notes the work underway at EREF to develop a list of composting facilities. We look forward to reviewing that work, when it is complete, for potential incorporation into the subsequent Inventory report as appropriate.

Comment 49: Datasets Available on Industrial Composting Facilities.
Please comment on datasets available on industrial composting facilities.

We are not aware of a comprehensive list of all industrial composting facilities in the U.S. and U.S. territories; however, the US Composting Council (USCC) has a list of facilities. It is not complete as not all facilities in the US are members of USCC. https://compostingcouncil.org/participants/

Biocycle Magazine runs this listing site: http://findacomposter.com/

Response: EPA appreciates commenter's feedback on the current lack of a comprehensive database of composting facilities. EPA has reviewed the Biocycle Magazine listing site and has found it to be incomplete as the commenter noted.

Comment 50: Industrial Composting Datasets
[actually, a composting question…]"Please comment on datasets available on industrial composting facilities located in the U.S. territories of Puerto Rico, Guam, U.S. Virgin Islands, Northern Mariana Islands, and American Samoa. We are aware of composting facilities in Puerto Rico. In order to accurately estimate GHG emissions from these facilities, data are needed on the first year of operation, approximate annual quantities processed or number of households serviced, and whether the amount of waste composted is consistent from year to year. "

Other than composting information available in: Goldstein, N., C. Coker, and S. Brown. 2014. State of Composting in the U.S.: What, Why, Where & How. Washington, DC: Institute for Local Self-Reliance. I am not aware of any such datasets. As discussed in more detail below in comments pertaining to Question 2. below, apart from issues raised above regarding an improved methodology for landfill methane emissions, there is a critical need to NATIONALLY develop an improved, annually updated, statistically-astute database to track the various waste streams in the United States (source, physical and chemical characteristics, mass, treatment and/or disposal strategy, imports & exports). For several decades, the EPA methodology for tracking waste in the U.S. related back to a 1970's era "material flow model" first developed by Franklin & Associates. There wasn't any comprehensive publically-available updated information on this methodology beyond the first few years of its application—most certainly, societal "material flows" have varied greatly in the intervening years. Importantly, the reported EPA annual numbers for total U.S. waste or landfilled waste over a number of years using the "material flow" approach typically summed to considerably less [approx. 50-60%] than independent compilations by others, for example, 1) the discontinued historic Biocycle Magazine/Columbia Univ. "State of Garbage" reports using state-reported totals and, more recently, 2) Powell, J. et al., 2016, Estimates of solid waste disposal rates and reduction targets for landfill gas emissions. Nature Climate Change, Volume 6, Issue 2, pp. 162-165. Powell et al. summed reported GHGRP data specifically for landfilled waste, reporting on significantly higher totals than EPA's annual reporting.

As valid decisions going forward regarding waste management policy, practices, and regulations cannot be made without credible data, EPA should develop and maintain a comprehensive database on U.S. waste generation, transport, recycling/reuse, and disposal as part of general record-keeping for U.S. waste management practices. Coordinating this compilation with the various state agencies would be a useful first step; however, given the diversity of state practices and procedures, Federal oversight is greatly desirable for achieving a minimum compliance level for record-keeping across all the states. EPA is undoubtedly familiar with Eurostat—the statistics agency within the EU which, for waste, annually tracks a large number of waste streams for the EU countries (municipal, industrial, agricultural, mining, forestry, etc.). I would recommend emulating and, indeed, coordinating with Eurostat to similarly track U.S. waste. Further information can be obtained at:

https://ec.europa.eu/eurostat/web/waste/overview
https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics
https://ec.europa.eu/eurostat/web/environment/waste.

In general, the U.S. is at a disadvantage in this age of metadata because we lack a national statistics agency such as Eurostat.

Response:* EPA appreciates commenter's feedback on the current lack of a comprehensive database of composting facilities and general lack of recordkeeping on waste management practices in the U.S. EPA has reviewed the Institute for Local Self-Reliance publication and has found it useful for certain information on state and municipal composting legislation and activities, but not as a comprehensive listing of facilities as would be needed to create a more detailed estimation of emissions from composting nationwide. We agree that a comprehensive database as outlined in the feedback would no doubt facilitate improving and updating these estimates for the Inventory, but note that initiating such an effort would not be justified for the Inventory alone and would involve budgetary decisions that go far beyond the scope of this report. At current activity levels, these emissions are 3% of the waste sector emissions. With existing resources, consistent with IPCC good practice, EPA needs to prioritize time and resources for future improvements on significant emission and removal categories (or key categories). Nevertheless, we will continue to review and incorporate the best available data in future reports given changing trends in this category.

Comment 51: Industrial Food Processing Waste Datasets

"Please comment on datasets that detail the quantities of industrial food processing waste that is disposed of in industrial waste landfills. The GHGRP dataset for industrial waste landfills includes select food processing facilities, however this dataset is not representative of the entire food processing sector. The Inventory methodology applies a disposal factor to the annual amount of foods processed. Currently, we do not have a representative data set for this sector with which to improve the methodology. "

I would recommend surveying major food processing companies and food technology consultants. The information you seek is not likely to be readily available and thus will require some EPA investment in time and resources to dig it out, organize it, and develop a strategy for annual updates. Therefore, it is highly recommended that food waste tracking be initiated for both "industrial" and "domestic" waste landfills. As above, I would highly recommend consulting existing Eurostat databases and emulating the Eurostat system for the U.S. going forward to includes multiple types of industrial, agricultural, forestry, domestic, construction/building and other waste streams. That would insure compatibility across much of the developed world with regard to waste statistics.

***Response:* EPA appreciates commenter's feedback on lack of available data on industrial food processing waste and agrees that obtaining this data would require significant resources and effort.**

Comment 52: Generation and Disposal Data: States and Municipalities Composting

Page 7-34, lines 20-31- this paragraph doesn't mention the rise of states and municipalities composting food waste and the handful of bans that address specifically that. It focuses on yard waste, but it seems like it should at least mention the rise of food waste composting. (CB)

Response:* EPA notes commenter's suggestion to add information about food waste composting trends and state and municipal bans on food waste disposal also influencing those trends. EPA will

add text regarding these trends in subsequent Inventory reports as applicable to describe related GHG-emissions trends.

Comment 53: Planned Improvements for Composting
Page 7-36, in the Planned Improvements section (for composting), they discuss wanting to collect more information on composting including quantity of waste composted, households served, etc. I think we could point them to some existing and soon to be released resources that would help. Happy to put that together or just call the appropriate person in OAR to discuss. (CB)

Response: EPA appreciates commenter's offer to provide resources on composting and will contact the commenter to obtain this information.

Comment 54: Generation and Disposal Data: Composted Waste Data Source
On page 7-34, line 9, it says from 1990 to 2017 the amount composted in the US went from 3,810 kt to 21,333 kt. What is the source of this data? (HP)

Response: As stated in the Methodology section of Section 7.3 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017, "estimates of the quantity of waste composted (M) are presented in Table 7-20*Error! Reference source not found.* ***for select years. Estimates of the quantity composted for 1990, 2005, 2010, and 2014 to 2015 were taken from EPA's Advancing Sustainable Materials Management: Facts and Figures 2015 (EPA 2018); the estimate of the quantity composted for 2012 to 2013 was taken from EPA's Advancing Sustainable Materials Management: Facts and Figures 2014 report; the estimate of the quantity composted for 2011 was taken from EPA's Municipal Solid Waste In The United States: 2012 Facts and Figures (EPA 2014); estimates of the quantity composted for 2016 and 2017 were extrapolated using the 2015 quantity composted and a ratio of the U.S. population growth between 2015 and 2016, and 2016 to 2017 (U.S. Census Bureau 2016, 2017, and 2018)."***

Appendix A: List of Reviewers and Commenters

EPA distributed the expert review chapters of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017* to a list of 326 expert reviewers across all sectors of the Inventory. The list below includes names of those expert reviewers who submitted comments as part of the Expert Review Period.

- Marci Baranski - United States Department of Agriculture (USDA), Office of the Chief Economist
- Jean Bogner - University of Illinois at Chicago - Dept. of Earth & Environmental Sciences
- Amy Van Kolken Banister - Waste Management, Republic Services, National Waste & Recycling Association, Solid Waste Association of North America, SCS Engineers, and Weaver Consulting Group
- Kerry Kelly - Waste Management, Republic Services, National Waste & Recycling Association Solid Waste Association of North America, SCS Engineers, and Weaver Consulting Group
- Barry Malmberg - National Council for Air and Stream Improvement, Inc.
- Bryan Staley - Environmental Research & Education Foundation
- Debra Kantner - Environmental Research & Education Foundation
- U.S. EPA's Office of Resource Conservation and Recovery
- Kate Zook - USDA Office of Energy and Environmental Policy
- G. Philip Robertson - Michigan State University - Dept. of Plant, Soil and Microbial Sciences & W.K. Kellogg Biological Station
- Richard A. Kohn - University of Maryland
- David W. Cooke, Ph.D.- Senior Vehicles Analyst, Union of Concerned Scientists
- Hendrik van Oss – (Retired) United States Geological Survey, National Minerals Information Center

Note: Names of commenters are listed in no particular order.

Appendix B: Dates of review

- Agriculture, Energy, Industrial Processes and Product Use (IPPU), and Waste: October 16 – November 14, 2018
- Land Use, Land Use Change and Forestry (LULUCF): November 9 – December 3, 2018

Appendix C: EPA Charge Questions to Expert Reviewers

To facilitate expert review and indicate where input would be helpful, the EPA included charge questions for the Expert Review Period of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017* report. EPA also noted to expert reviewers that while these charge questions were designed to assist in conducting a more targeted expert review, comments outside of the charge questions were also welcome. Included below is a list of the charge questions by Inventory chapter.

Energy

General Questions:

1. Please provide your overall impressions of the clarity and transparency of the Energy chapter.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Energy chapter.

Source Specific Questions:

Fossil Fuel Combustion: CO_2 from Fossil Fuel Combustion

1. Please provide your overall impressions of the clarity of the discussion on trends in CO_2 emissions from fossil fuel combustion. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity.
2. Data for energy use in U.S. Territories comes from the International Energy Statistics provided by EIA. This source has data only through 2014, the years 2015 through 2017 are proxies. Are there other sources of U.S. Territory energy use that could be used?
3. Facility-level combustion emissions data from EPA's GHGRP are currently used to help describe the changes in the industrial sector. Are there other ways in which the GHGRP data could be used to help better characterize the industrial sector's energy use? Are there ways the industrial sector's emissions could be better classified by industrial economic activity type?

Fossil Fuel Combustion: CH_4 and N_2O from Stationary Combustion

1. The CH_4 and N_2O emission factors for electric power sector are based on a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. The emission factors are primarily taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Are there other more U.S.-specific CH_4 and N_2O emission factor data sources that could be utilized, especially for natural gas combustion sources?

Carbon Emitted from Non-Energy Uses of Fossil Fuels

1. Please provide your overall impressions of the clarity of the discussion on Carbon Emitted from Non-Energy Uses of Fossil Fuels. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity, especially in regards to links with the IPPU chapter.

Mobile Sources

1. Please provide your overall impressions of the clarity and transparency of the proposed mobile source updates.

2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the proposed mobile source updates.

Methodology for Estimating Electricity Use by On-Highway Electric Vehicles

Previous versions of the Inventory allocated electricity use, and associated emissions, between economic sectors based on electricity sales data provided by the industry through U.S. Energy Information Administration (EIA) reports. The data for electricity used in the Transportation Sector only includes electricity used for railroads and railways. Electricity used to charge electric vehicles currently fall under the Residential and Commercial Sectors associated with home and public charging stations. Due to the increasing numbers of electric vehicles (EVs) in the United States, EPA has developed a method to estimate the portion of total electricity used to charge electric vehicles, and to re-allocate that portion of electricity and emissions from the Residential and Commercial Sectors of the Inventory to the Transportation Sector. The proposed methodology would not impact total electricity production or emissions; only the allocation of electricity across the Transportation, Residential, and Commercial Sectors is impacted.

1. The proposed update uses monthly vehicle sales data to estimate nation-wide populations of BEV and PHEV vehicles. Fleet data from EIA are used to estimate populations of neighborhood electric vehicles and electric buses. Are there other population data sources EPA should consider for this update?
2. The outlined methodology uses FHWA Highway Statistics' "Average miles traveled per vehicle" to estimate annual vehicle miles traveled (VMT) by BEVs and PHEVs. This average – around 11,300 miles per vehicle in 2015 and 2016 – includes vehicles of all fuel types (e.g., gasoline, diesel, electricity, compressed natural gas, propane). Is it reasonable to apply this annual VMT statistics to electric vehicles? Are there other data sources which could be used to derive annual VMT by BEVs and PHEVs?
3. The proposed update requires reallocating emissions from the Residential and Commercial Sectors of the Inventory into the Transportation Sector. EPA has used an 85% residential/15% commercial split based on a technical report from Idaho National Laboratory to reassign these emissions. Is this a reasonable split of the emissions? Are there other studies on the location of charging EVs?

Industrial Processes and Product Use (IPPU)

***General Questions*:**

1. Please provide your overall impressions of the transparency of the IPPU chapter.
2. Please provide any recommendations of improvements that EPA can consider to improve the completeness and/or accuracy of the IPPU chapter.
3. For the source categories included in the expert review draft, is the state of the industry current and accurately described? Are there technologies, practices, or trends that EPA should consider?

***Source Specific Questions*:**

Minerals Production

1. **Other process uses of carbonates -** Please provide input on:
   - Data on carbonate use in non-metallurgical magnesium production.
   - Data on carbonate use in the production of ceramics.

Chemicals Production

2. **Caprolactam, Glyoxal and Glyoxylic Acid Production** - With the inclusion of this new IPPU source category as of last Inventory, EPA requests feedback on the overall chapter text, assumptions and information on the state of the industry.
3. **Calcium Carbide Production** - Please provide input on data sources and industry information on production to estimate emissions using IPCC methods.

Metals Production

4. The EPA seeks comments on assumptions applied to determine the split between primary and secondary zinc production based on U.S. Geological Survey national totals. Are other options/data sources available to distinguish between process production totals?

Other IPPU Categories

5. **N_2O Product Use** - Please provide input on recent/alternative production statistics for various N_2O product use subcategories listed within the Nitrous Oxide from Product Uses source chapter.
6. **ODS Substitutes -** The EPA seeks comments on possible sources of hydrofluorocarbon (HFC) use that are not reflected, or whose use is modeled lower than actual, as evident from a comparison of the underlying model with data reported under EPA's Greenhouse Gas Reporting Program (GHGRP).
7. **Semiconductor Manufacturing -** In addition to general comments on the semiconductor inventory, EPA is specifically seeking input on the items outlined below, which discuss recent methodological changes in the inventory to account for:

    i. Emissions from the non-reporting population.
    ii. Changes in the Subpart I emission factors and default destruction or removal efficiencies between the 2013 and 2014 reporting years.

More details on the targeted semiconductor manufacturing specific feedback are included below.

Semiconductor Manufacturing Targeted Feedback

7.i) Input on Estimating emissions from the non-reporting population of the semiconductor industry.
In 2017, EPA developed a new approach for estimating emissions for the segment of the semiconductor industry that does not report through EPA's GHGRP, Subpart I (Electronic Manufacturing) for the 1990-2016 Inventory. This same method has also been applied in the 1990-2017 Inventory. This approach is described in the accompanying Semiconductor Inventory Chapter text. In addition to seeking experts' comment on the approach, EPA is requesting feedback on the following:

7.i.1. Method for Development of Emission Factors for Non-GHGRP Reporting U.S. Semiconductor Population.

EPA develops emission factors using emissions data reported from the GHGRP (Subpart I); information on the use of abatement from the GHGRP (Subpart I); and activity data (substrate area and manufactured layers) from the World Fab Forecast, Census Bureau[1], and the *International Technology*

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[1] United States Census Bureau (USCB) *Historical Data: Quarterly Survey of Plant Capacity Utilization*. Available online at: <https://www.census.gov/manufacturing/capacity/historical_data/index.html>.

Roadmap for Semiconductors. With this information EPA develops emission factors in the units of emissions per total manufactured layer area (TMLA), for each year, for both 200 mm and 300 mm wafer sizes, for each fluorinated greenhouse gas (F-GHG) and N_2O. EPA is considering one of the following two approaches to develop these emission factors:

- Approach 1 - Weighted averages (by wafer size, year, and gas type), calculated as total emissions divided by total TMLA (currently used for 2015 and 2016); or
- Approach 2 - Regression analyses (by wafer size, year, and gas type), based on a regression through the origin analysis.
  a. Which approach would semiconductor manufacturing experts suggest using to calculate emission factors? Alternatives?
  b. Do you agree that the best approach to developing emission factors is based on wafer size as opposed to other characteristics such as substrate type?

7.i.2. Data Sources for Development of Emission Factors for Non-GHGRP Reporting U.S. Semiconductor Population.

EPA relies on the number of layers by nodes defined in the Technology Roadmap to estimate TMLA. The number of layers currently used in the inventory are from the tables supporting the most recently available roadmap (2015).[2]

a. Please provide feedback on whether these numbers are accurate, or whether they should be adjusted? If they should be adjusted, how would you suggest adjusting them?

7.ii) Addressing time series consistency issues with the Subpart I emission factors and default destruction or removal efficiencies.

Changes to the default emission factors and default destruction or removal efficiencies (DREs) used for GHGRP reporting affected the apparent emissions trend between 2013 and 2014. These changes did not reflect actual emission rate changes but data improvements. Therefore, for the Expert Review Draft of the 1990-2017 Inventory, EPA adjusted the time series of GHGRP-reported data for 2011 through 2013 to ensure time-series consistency using a series of calculations that took into account the characteristics of a facility (e.g., wafer size and abatement use). This approach is described in the accompanying Semiconductor Inventory Chapter text. The graph below compares the adjusted time series from the Expert Review Draft of the 1990-2017 Inventory to the unadjusted time series from the 1990-2016 GHG Inventory.

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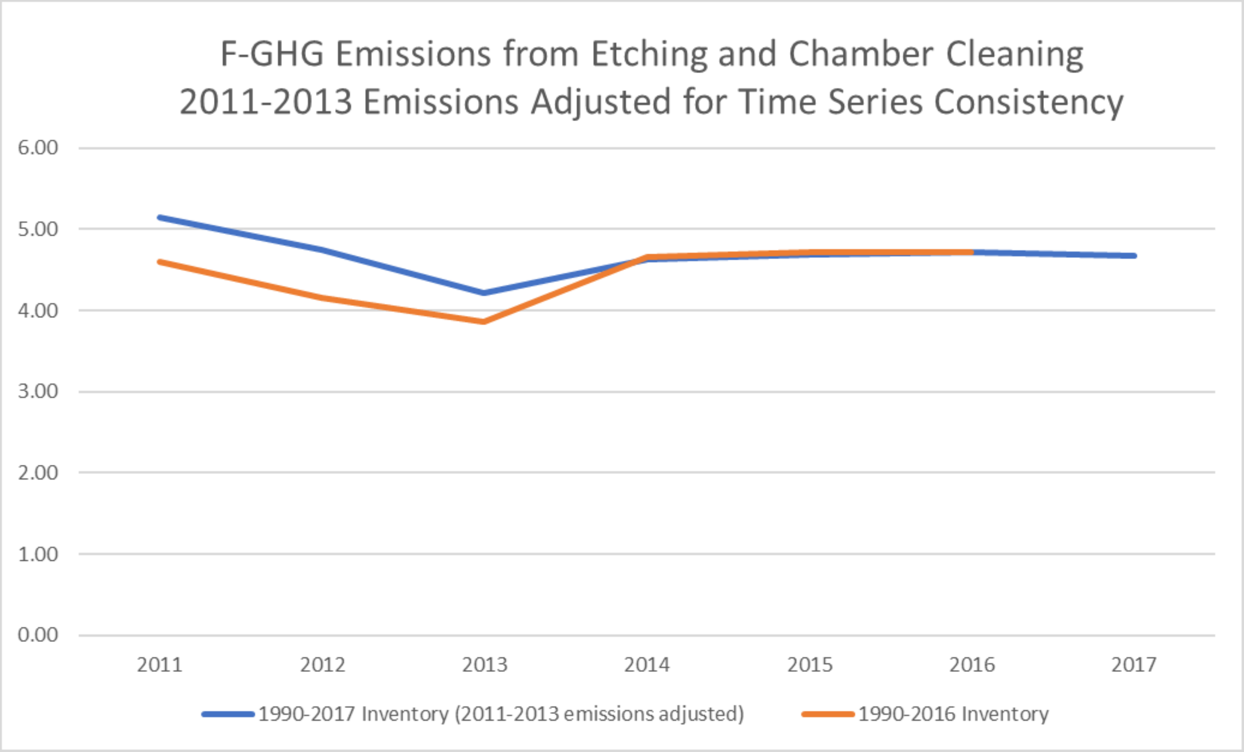
[2] https://www.dropbox.com/sh/3jfh5fq634b5yqu/AAD7uR0pBadu8-bsMAlN9TQUa/2015%20ITRS%202.0%20FT%20TABLES?dl=0&subfolder_nav_tracking=1



In addition to seeking experts' comment on the approach, EPA has the following specific questions:

a. Would you suggest any adjustments to the assumed site-specific DREs used in the readjustment calculations?

EPA assumed site-specific DREs were as follows:

Gas	**Process Type**	**Assumed Site-Specific DRE**
CF4	Etch	90%
All Other Gases	Etch	98%
NF3	Clean	95%
CF4	Clean	80%
All Other Gases	Clean	80%

b. Do expert reviewers have suggestions for alternative approaches for adjusting 2011-2013 emissions for fabs and facilities which abate and report to the GHGRP? Specifically, EPA is seeking feedback on the amounts of gas assumed to be abated in the adjustment analysis as well as the use of the fab-wide DRE from 2014 to aid in the adjustment calculations for 2011-2013. EPA can provide fab or facility-specific data to help aid in reviews if requested. As a reminder:

   - To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first calculated the quantity of gas abated in 2014 using reported F-GHG emissions, the revised default DREs (or the estimated site-specific DRE, if a site-specific DRE was indicated), and the fab-wide DREs reported in 2014.
   - EPA then estimated the quantity of NF_3 abated for remote plasma clean in 2014 using the

ratio of emissions reported for CF_4 (which is not abated) and NF_3. This abated quantity was then subtracted from the total abated quantity calculated above.

- To account for the resulting remaining abated quantity, EPA assumed that the percentage of gas passing through abatement systems was the same across all remaining gas and process type combinations where abatement was reported for 2014.
- The percentage of gas abated was then assumed to be the same in 2011-2013 (if the facility claimed abatement that year) as in 2014 for each gas abated in 2014.

c. For facilities that have more than one fab, do expert reviewers have suggestions on how to calculate facility-wide DREs from the fab-wide DREs reported for 2014? (Emissions and other parameters were only reported at the facility level before 2014). We currently use the straight average of the fab-wide DREs.
d. For fabs that have multiple wafer sizes in the same fab, do expert reviewers have suggestions on how we should allocate emissions to each wafer size? We assumed that emissions were split 50/50 if there was no other information to go on. Note that in general, the time series adjustment *decreases* 2011-2013 estimated emissions for 300-mm fabs while it *increases* 2011-2013 estimated emissions for 200-mm fabs.
e. If possible, EPA would appreciate it if experts could share data to support their comments on how the changes in emission factors and DREs between the 2013 and 2014 GHGRP reporting years impacted GHG emissions, and/or any data to help support comments and feedback on EPA's proposed method for adjusting GHGRP emissions from 2011-2013.

Agriculture

General Questions:

1. Provide your overall impressions of the clarity and transparency of the Agriculture chapter.
2. Provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Agriculture chapter.
3. Provide feedback on the methodologies, assumptions and activity data used to estimate emissions for categories within the Agriculture chapter.

Source Specific Questions:

1. For the Manure Management source category, is the state of the industry current accurately described? Are there other technologies, practices, trends that we should consider?
2. Are the parameters and discussion of uncertainty within the Manure Management source category estimates adequately reflecting all uncertainties from this industry and the data EPA is currently using?
3. The Manure Management source category relies on national/regional livestock production and management data for calculating emissions estimates from USDA APHIS and NASS. Are there other/newer data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    - Waste management system data, particularly seasonal changes in emissions from different WMS
    - Maximum methane producing capacity
    - Volatile solids and nitrogen excretion rates
    - Measured emission estimates (by waste management system) to help refine estimates of methane conversion factors
4. For the Enteric Fermentation source category, is the state of the industry current and accurately

described? Are there other technologies, practices, trends that we should consider?

5. The Enteric Fermentation source category relies on national/regional livestock production, diet and management data for calculating emissions estimates. Are there other/newer data sources or methods that EPA should be aware of and consider in the calculating these emissions? Especially for:
    - Dry matter/gross energy intake
    - Annual data for the DE, Y_m, and crude protein values of specific diet and feed components for foraging and feedlot animals
    - Monthly beef births and beef cow lactation rates
    - Weights and weight gains for beef and dairy cattle

6. For the Enteric Fermentation source category and the Cattle Enteric Fermentation Model (CEFM), are the various regional designations of U.S. states (as presented in Annex 3.10) used for characterizing the diets of foraging cattle appropriate? The CEFM is used to estimate cattle CH_4 emissions from enteric fermentation, and incorporates information on livestock population, feeding practices, and production characteristics.

Land Use, Land-Use Change, and Forestry (LULUCF)

General Questions:

1. Provide your overall impressions of the clarity and transparency of the categories provided in the LULUCF chapter.
2. Provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the LULUCF chapter.
3. Provide feedback on the methodologies and activity data used to estimate emissions for categories within the LULUCF chapter.

Category Specific Questions:

1. For Forest Land Remaining Forest Land category, are the methods used to estimate carbon stock changes on forest lands in interior Alaska as well as the new state-level methodology used to estimate carbon stock changes on forest lands in western states appropriate and clearly described?
2. For Settlement Trees (formerly Urban Trees), is the new approach using the settlement area from the land representation in the GHG Inventory and percent tree cover applied to developed land from NLCD an appropriate methodology and clearly described?
3. For the Yard Trimmings and Food Scraps category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider?
4. For the Yard Trimmings and Food Scraps category, are there other data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    - C storage, decay rates, etc. for yard trimmings and food scraps
    - Decay rates of food scraps, leaves, grass, and branches
    - National yard waste compositions
    - Precipitation range percentages for populations for the decay rate sensitivity analysis

Waste

General Questions:

1. Please provide your overall impressions of the clarity and transparency of the Waste chapter.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Waste chapter.

Source Specific Questions:

Wastewater

1. The wastewater source category relies on national production data from a variety of sources for calculating emissions estimates. Are there other data sources that EPA should be aware of and consider in the emissions calculations of this source?
2. Please provide input on any additional sources of wastewater outflow or BOD production that we may not consider in our industrial methane emissions calculations. Do our estimates of the percent of wastewater treated anaerobically seem reasonable?
3. For domestic wastewater emissions, please provide input on:
    a. Any additional sources for the N content of sludge, amount of sludge produced, and sludge disposal practices.
    b. National Level data on the type of wastewater treatment systems in operation,
    c. National level data on the biogas generations and recovery operations,
    d. The estimates of the percent of BOD removed by aerobic, anaerobic, and other treatment systems for our methane estimates,
    e. The protein estimates and overall calculations for nitrous oxide. For example, do you have suggestions for developing a country-specific factor, rather than the IPCC default factor, to estimate the amount of nitrogen from industrial and commercial sources co-treated with domestic wastewater? and
    f. Sources of data for development of a country-specific methodology for N_2O emissions associated with on-site industrial wastewater treatment operations, including the appropriateness of using IPCC's default factor for domestic wastewater (0.005 kg N_2O-N/kg N).
4. Are there additional industries that are sources of methane or nitrous oxide emissions that should be included in the wastewater inventory? Are there available sources of national-level data for these industries?
5. Do you have suggestions for improving the discussion of our methodology? Is there any additional information that should be included to provide additional transparency?
6. Is the state of domestic and industrial wastewater treatment current and accurately described?

Landfill Specific

1. Please comment on datasets available on industrial composting facilities located in the U.S. territories of Puerto Rico, Guam, U.S. Virgin Islands, Northern Mariana Islands, and American Samoa. We are aware of composting facilities in Puerto Rico. In order to accurately estimate GHG emissions from these facilities data is needed on the first year of operation, approximate annual quantities processed or number of households serviced, and whether the amount of waste composted is consistent from year to year.
2. Please comment on datasets that detail the quantities of industrial food processing waste that is disposed of in industrial waste landfills. The GHGRP dataset for industrial waste landfills includes select food processing facilities, however this dataset is not representative of the entire food processing sector. The Inventory methodology applies a disposal factor to the annual amount of foods processed. Currently, we do not have a representative data set for this sector with which to improve the methodology.
3. A comprehensive Internet search by state was conducted to identify waste characterization studies published as of July 2018. We plan to conduct analyses to generate DOC values specific to the time frame of 1990 to 2004. This time frame is specified because the Inventory uses directly reported

GHGRP net emissions, which incorporate the DOC values allowed under the rule, in years beyond 2004. Please comment and provide information on any additional studies that have not been published on the Internet from 1990 to date that may further these efforts.

4. An analysis is being conducted on decay rate values reported by developed countries (e.g. UNFCCC Annex 1 countries) in their annual National Inventory Reports, as well as decay rate values used as defaults in first order decay models, as compared to the U.S. Greenhouse Gas Inventory defaults used in the U.S. Waste model. This analysis is specific to the 1990 to 2004 time frame, because the Inventory uses directly reported GHGRP net emissions, which incorporate the decay rate values allowed under the rule, for years beyond 2004. Please comment and provide information on any additional studies and models that have not been published on the Internet from 1990 to date if any stakeholders have this information available to share.

United States
Environmental Protection
Agency

Summary of Public Review Comments and Responses:
Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018*

May 2020
U.S. Environmental Protection Agency
Office of Atmospheric Programs
Washington, D.C.

Responses to Comments Received during the Public Review Period on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018*

Preface

EPA thanks all commenters for their interest and feedback on the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Per Federal Register Notice 2020-02139 published on February 12, 2020, EPA announced document availability and request for comments on the draft "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018" report. The EPA requested recommendations for improving the overall quality of the inventory report to be finalized in April 2020 and submitted to the United Nations Framework Convention on Climate Change (UNFCCC), as well as subsequent inventory reports.

During the 30-day public comment period which ended March 13, 2020, EPA received 17 sets of comments, including 34 unique comments in response to the notice. This document provides EPA's responses to technical comments on methods and data used in developing the annual greenhouse gas inventory. The verbatim text of each comment extracted from the original comment letters is included in this document, organized by commenter. Full comments can be found in the public docket here: https://www.regulations.gov/docket?D=EPA-HQ-OAR-2019-0706. EPA's responses to comments are provided immediately following each comment excerpt.

Commenter: American Fuel and Petrochemical Manufacturers (AFPM)

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0009

David Friedman

Comment 1: Re: Percent of CO_2 from refining that results from flaring

This comment is in respect to the Energy chapter of the report, specifically on the section describing GHGs from the refining sector. On page 3-68, the report states, "Almost all (about 98 percent) of the CO_2 from refining is from flaring."[1] Based on previous reports issued by EPA, AFPM believes that this statement is inaccurate and contradicts determinations made in these previous reports.

In both the 2015[2] and 2019[3] Industrial Profile reports, EPA includes charts that summarize petroleum refinery sector GHG emissions by source (see Appendix below). The refinery GHG emissions by source include: Combustion of Fuel, (percentage share of 63 and 73 respectively), Catalytic Cracking/Reforming (approx. 23%), Flaring (approx. 2.5%), and other sources (such as Hydrogen Plant, Sulfur Removal Plant, etc.). The sum of the published 2015 and 2019 percentage shares of Combustion of Fuel, Catalytic Cracking/Reforming, and sources other than flaring total more than 97 percent.

As written, the 2020 report implies that the numbers are now transposed and that flaring now accounts for 98 percent of a refinery's GHG emissions. The calculations in the 2015 and 2019 reports are also more consistent with the refining industry's own determinations on the contribution of flaring to the overall GHG emissions in a refinery.

AFPM recommends that EPA reevaluate the refinery GHG summary and apply from the earlier reports the determination that flaring contributes a very small portion (less than 2.5%) to a refinery's overall GHG emissions.

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[1] Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2018, 3-68.

[2] Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Petroleum Refining Industry. (2010). Retrieved 10 March 2020, from https://www.epa.gov/sites/production/files/2015-12/documents/refineries.pdf.

[3] Greenhouse Gas Reporting Program Industrial Profile: Petroleum Refineries Sector (2019). Retrieved 10 March 2020, from https://www.epa.gov/sites/production/files/2019-10/documents/petroleum_refineries_industrial_profile_9_25_2019.pdf.

APPENDIX

2015 Industrial Report

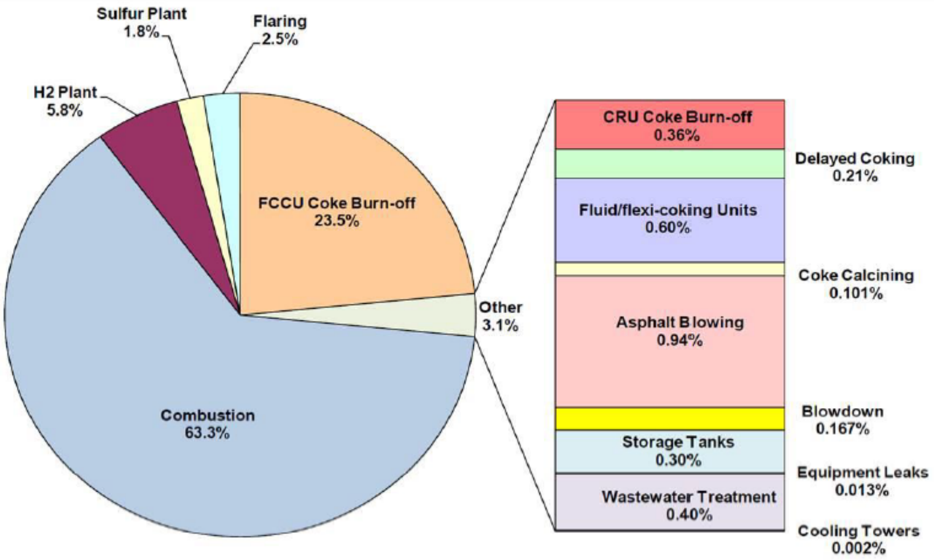
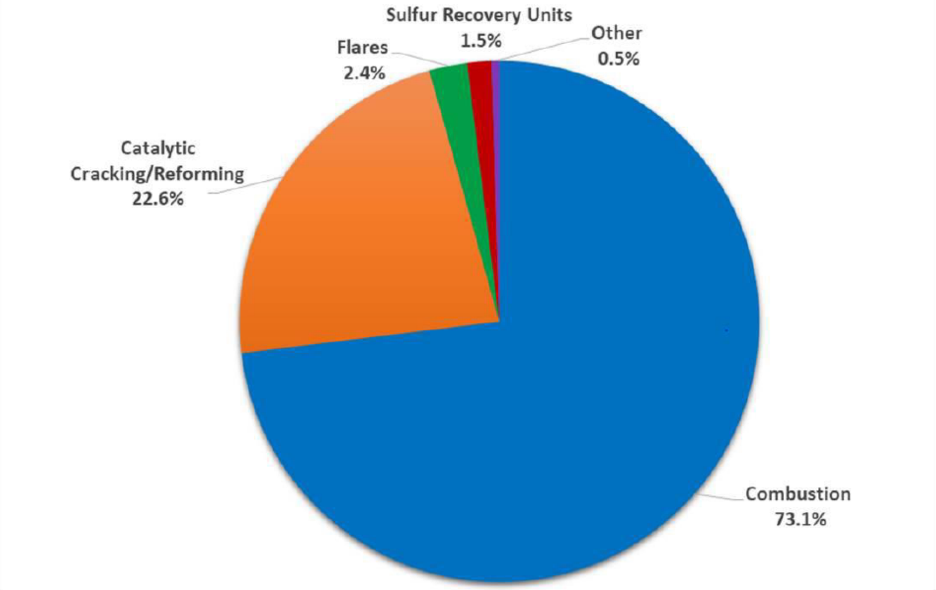


Figure 2. Contribution of different emission sources to the nationwide CO_2 equivalent GHG emissions from petroleum refineries.

2019 Industrial Report

FIGURE 1: 2017 PETROLEUM REFINERIES SECTOR: EMISSIONS BY SOURCE[a, b]



Response: The Inventory text in Section 3.6 on Petroleum Systems has been edited to clarify that the emissions discussed in this section are fugitives (leaks, venting, and flaring), not combustion sources. See pp. 3-68 to 3-70 in Section 3.6 of the report.

Commenter: American Gas Association

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0010

Pamela Lacey

Comment 2: Re: Emission estimates for Natural Gas Systems

The GHGI directly affects AGA and its members because it provides the best available estimate of national average GHG emissions from our members' operations – including natural gas local distribution, transmission, and storage. In addition, the GHGI also provides the best available estimate of the national average methane intensity of the product our members deliver to customers, measured from wellhead to the customer. As demonstrated by previous Inventories, the methane intensity of delivered natural gas in the U.S. already falls well below even the most stringent thresholds for immediate climate benefits achieved through coal to natural gas switching.[4]

As the 2020 Draft GHGI shows, natural gas emissions from distribution systems have declined by 73 percent from 1990 through 2018, including an almost 1% additional reduction between 2017 and 2018. This emissions reduction has been achieved largely through replacing cast iron and unprotected steel distribution mains with modern medium and high-density polyethylene (MDPE or HDPE) or cathodically protected steel pipe and upgrading metering and pressure regulating stations to replace high bleed pneumatic devices. Increasingly, our members are also seeking additional opportunities to reduce emissions, for example through their commitments in the EPA Methane Challenge program to reduce emissions from pipeline blowdowns or to enhance programs for reducing pipeline dig-ins (third party damage). We look forward to seeing how these emission reduction efforts can be reflected in future GHGIs.

AGA appreciates EPA's ongoing efforts to improve emission estimates based on new research. While the 2020 Draft GHGI contains no proposed changes in methodology for estimating emissions from natural gas distribution, transmission or storage,[5] AGA appreciates and supports EPA's proposals to update emission estimates for upstream and midstream segments of the natural gas supply chain to incorporate data from recent studies and from reporting under EPA's GHG Reporting Program (GHGRP). For example, AGA supports the use of updated GHGRP reported data in the exploration segment well completions with and without reduced emissions completions (RECs), demonstrating a 72% decrease in exploration emissions from 1990 through 2018 and an 8.3% reduction from 2017 to 2018.[6] AGA also supports EPA's use of updated methodology using GHGRP data and the Zimmerle et al. 2019 study to improve the estimate of emissions from gathering and boosting compressor stations in the production segment.[7]

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[4] See AGA's Analysis of EPA's 2019 GHGI (May 23, 2019) at https://www.aga.org/research/reports/epa-updates-to-inventory-ghg-may-2019/.

[5] See 2020 Draft GHGI at page 3-98.

[6] See 2020 Draft GHGI at page 3-83.

[7] See 2020 Draft GHGI at pages 3-83 and 3-91.

Response: EPA appreciates the comment and has noted potential use of data from the Methane Challenge program in the planned improvements text for Natural Gas Systems. See page 3-101 of the report.

Commenter: American Petroleum Institute (API)

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0012

Karin C. Ritter

Comment 3: Delayed Cokers in Refining

API has advocated the use of GHGRP data for the refining sector (Subpart Y) since all U.S. refineries have been required to report CH_4, CO_2, and N_2O emissions for all major activities starting with emissions that occurred in the year 2010.

For delayed cokers, an updated calculation method was promulgated by the U.S. EPA in December 2016, which became mandatory starting with reporting year 2018. The update to the calculation methodology resulted in higher reported methane emissions from delayed cokers in 2018 compared to previous years of reporting. API recognizes that the update did not impact all facilities reporting under Subpart Y equally, since some facilities had adopted the updated methodology earlier.

API concurs with EPA's approach to update the time series estimate for 1990-2018 using a ratio of reported delayed cokers and GHGRP emissions from 2017 to 2018 in order to ensure continued consistency of emissions estimated between the GHGI and GHGRP for the refining sector.

Response: EPA appreciates the comment.

Comment 4: Offshore Petroleum and Natural Gas Production

In previous discussions with EPA, API supported the continued use of updated Gulfwide Emission Inventory (GEI) data to ensure the utilization of the most current representation of activities and emissions for offshore operations. EPA has implemented this approach in the GHGI by calculating vent and leak EFs for offshore facilities in GOM federal waters for major complexes and minor complexes using Bureau of Ocean Energy Management (BOEM) GEI emissions data from the 2005, 2008, 2011, and 2014. EPA acknowledged that this approach addresses only production in the federal waters of the Gulf of Mexico (GOM). Notably, EPA considered a 4-step process of assigning production type for each complex. The approach potentially counts the same complex up to four times across the GEI's for 2005, 2008, 2011, and 2014.[8] It is unclear as to how the number of complexes counted were reconciled with the BOEM GEI Inventory and which number of complexes were used in order to achieve the results in the Draft GHGI 2020 update (Table 3-48 of Draft GHGI). The complex counts and approach should be reconciled with BOEM and explained as to how the total complex counts were used.

Additionally, BOEM GEI had a step-change in their reporting process which incorporated more minor sources from 2005 to 2008. EPA should note if that step-change or other main factors were the driver(s) for the increase in the number of complexes. EPA should further note that the "increase" in CO_2 emissions between 2005 and 2018 was the result of more comprehensive reporting and changes in

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[8] U.S.EPA (2019), "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Updates Under Consideration for Offshore Production Emissions", September 2019 (Table 4, page 8).

emission factors. Lastly, it would be beneficial to understand whether EPA's emissions trends over this period accounted for a 50% reduction in platforms and an 80+% reduction in well starts.

API contends that using source specific emission factors may be preferable to the approach taken by EPA of defining major and minor 'complexes' along with major or minor 'structures', and assigning average emissions to each type of complex. This approach is not fully transparent regarding the process used for assigning the emission sources to the complex categories and calculating the respective emission factors.

Concurrently, EPA calculated GOM federal waters flaring emissions using flaring volumes reported in Oil and Gas Operations Reports (OGOR), Part B (OGOR-B). EPA's approach used the EF basis of kg/MMBtu (with year-specific heat content), applying it to OGOR-B flared gas volumes. The other option was to use BOEM's GEI emission factors however, according to the EPA, this was not chosen because OGOR-B flared gas volume data are available each year, versus the GEI data that is available only during publication years, However, BOEM already collects and assesses emissions based on OGOR-Data. BOEM completed an in-depth QA/QC of GOADS-2011 data submittals for volumes vented and flared with the values reported to the Office of Natural Resources Revenue (ONRR) through Oil and Gas Operations Report (OGOR) forms. Additionally, BOEM contacted operators and reconciled flare/vent estimates. Given this extensive review, it is appropriate to use BOEM emission factors and not duplicate an existing effort. Furthermore, BOEM is in the process of developing a new web-based emissions reporting tool. BOEM anticipates collecting emissions data using the new web-based reporting tool for CY2021 and for those emissions to be reported annually.

API welcomes EPA's discussion of the fact that the previous Inventory allocated all GOM federal waters flaring emissions to offshore gas production facilities, which explains the shifting of estimated emissions between the petroleum and natural gas systems in the GHGI. Moreover, in order to combine its GHGI and OGOR-B datasets, EPA assumed that the 2011 OGOR values, which indicate that 80% of flared gas is from oil complexes and 20% of flared gas is from gas complexes, is broadly representative and applied it to all prior years (1990-2010) that were originally attributed to all gas flaring. This is due to the fact that separate volumes of gas flared and gas vented were not available prior to 2011 and EPA relied on data provided by the Minerals Management Service (MMS) Staff from 1990-2008. API contends that it is appropriate and more representative to allocate flaring to both offshore oil and gas complexes, however the methodology of percent (%) allocation of flared gas from oil vs gas complexes should be reviewed versus BOEM and their historical MMS data to assess EPA's selection of the 80%/20% assignment.

API is also noting that new data is becoming publicly available on oil and gas venting and flaring. Clearly the trend favors flaring (vs. venting) because most gas is now produced at modern deepwater facilities. A 2017 Bureau of Safety and Environmental Enforcement (BSEE) report[9] (Tables 1 and 2) confirms that oil-well gas is primarily flared (in those instances when not captured and exported to market) and that nearly all the gas released from floating deep-water structures is flared. Given the much higher GHG effect of methane (vs. CO_2), this is a very important distinction and highly favorable trend.

The U.S.EPA included in the current GHGI calculations of production based EFs for offshore facilities in the Pacific and Alaska regions, using data from the GHGRP. API understands that under 40CFR 98.233 (s)(2)(i), production facilities in GOM State Waters, Pacific and Alaska Regions reporting to the GHGRP adjust previously calculated emissions using the duration of operations for calendar years that do not overlap with the most recent GEI. API concurs that the increase in CH_4 emission estimates from offshore oil production are due in part to the inclusion of emissions from facilities located in GOM state waters

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[9] https://www.bsee.gov/sites/bsee.gov/files/5007aa.pdf

and the Pacific and Alaska regions. API also notes that the increase in offshore emissions attributable to oil production is due to the fact that a much higher percentage of offshore facilities in the current Inventory are classified as oil rather than gas.

API requests further information for the EPA calculated GHGRP production-based emission factors in non-GEI years. The GHGRP methodology for non-GEI years requires the leaks, flaring, and fugitive emissions reported to be scaled based solely on operating hours. Subsequent scaling of operating hour based emissions by production volume might not be representative of actual emissions. Additionally, API is concerned that the use of production data from all sites in conjunction with emission factors that are limited to the largest emitting sites (those reporting to the GHGRP) might skew the emission estimate for the specific region.

API recognizes that the implementation of EPA's updated methodology results in decreases in CH_4 and CO_2 emissions from natural gas systems, due to the reallocation of venting and flaring emissions between the Petroleum and Natural Gas segments. Most notably, in previous GHGIs all CO_2 emissions from flaring were reported under Natural Gas Systems.

API notes that the major factors affecting the lower CH_4 and CO_2 emissions from offshore production include:

- Reductions in methane emissions from offshore operations can be directly related to more stringent limitations imposed by BSEE related to venting and flaring. Venting and flaring is limited by 30 CFR 250 Subpart K which often required the installation of separate flare and vent meters (after May 2010) and limits the amount of flaring/venting allowed. In addition, in 2012, BSEE issued guidance for requesting departure approval to flaring or venting beyond allowable. No flaring or venting without permission is allowed except in limited circumstances, permitted on a case-by-case basis at BSEE's discretion. When considering requests to approve flaring or venting, BSEE does not consider the avoidance of lost revenue to be a justifiable reason.
- Industry as a whole is utilizing more VRU equipment to capture releases and moving away from venting and toward the safer alternative of flaring which results in overall lower methane emissions. As a consequence of this important development over the past 10 years less gas is being vented. Even though oil-well gas production (for which there may be a greater incentive to flare) now (since 2016) exceeds gas-well gas production, the volume of gas flared or vented has declined. While total gas production has also declined, total flaring/venting volumes have remained relatively stable at around 1% of total gas production.
- Removal of older platforms, mainly in shallow water and nearer to shore, and installation of new, state of the art platforms in deep water much further from shore.

Response: Additional documentation was provided in the memo, "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Updates for Offshore Production Emissions," clarifying how complex counts were developed.[10] Additional text was provided in the GHG inventory and the memo to clarify the data sources for complexes. The trends over time are due to the underlying trends in the complex counts and emissions as reported to BOEM. Emissions estimates were calculated using complex-level factors for offshore operations in GOM federal waters and using production-based emission factors for offshore operations in state waters. An estimate of emissions source-level emissions was developed using the fraction of emissions in each category in the GOM federal waters data set, applied to GOM federal and state water total emission estimates, and using the fraction of emissions in each category

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[10] https://www.epa.gov/sites/production/files/2020-04/documents/2020_ghgi_update_-_offshore_production_final.pdf

in GHGRP for Pacific and Alaska offshore production, and applied to the total estimates for Pacific and Alaska offshore production. The emission source-level estimates are available in the supplementary excel annex files for Petroleum and Natural Gas Systems.[11]

Regarding the use of emission factors calculated from data from the from the GHGRP reporting population for Pacific and Alaska offshore production, alternative data sources are unavailable.

Regarding the use of the GEI versus OGOR-B data, the emissions estimates were calculated using OGOR-B. GEI data is currently available for the years 2005, 2008, 2011, 2014, and 2017. The OGOR-B dataset can be used to calculate flaring emissions for the full 1990 to 2018 time series. EPA applied the OGOR-B data because it is more readily available across the full time series. EPA is aware the BOEM GEI studies may be updated more frequently in the future and will assess the data as it becomes available. Regarding upcoming availability of emissions data for offshore production, this feedback has been noted in the Planned Improvements section of the GHGI. See pages 3-82 and 3-101 of the report.

Comment 5: Gathering and Boosting Operations

API supports separating the GHGI emission estimate for G&B from the estimate for onshore production and natural gas processing. EPA updated the gathering and boosting (G&B) station emission estimation methodology based on CH_4 measurements at G&B stations and from data provided since 2016 under the GHGRP. EPA applied the national average ratio of compressors per station and the national-level scaling factor, both based on year 2017 data, from the Zimmerle et al. study and did not re-evaluate the ratio or scaling factor for other years in the public review draft of the Inventory.

API finds that using GHGRP developed equipment level emission factors for sources not included in the Zimmerle et al. field study is the best available data at this time. The U.S.EPA approach for scaling GHGRP emissions to the national level closely matches the Zimmerle et al. approach of scaling the Production sector data (1.07 compared to 1.075) for 2017. However, API contends that the Zimmerle et al. approach is the more conservative and preferred approach. The GHGRP Gathering and Boosting volume of gas received can be reflective of gas transported from one gathering station to another instead of new production from well sites. For example, the 2017 quantity of gas received for the G&B segment (44,187,605,033mscf) exceeds the total produced gas volume in DI desktop (33,755,773,191mcf based on 2017 DI Desktop data pulled in June2018).

The Zimmerle et al study found great variability in the compressor counts per station and in the fraction of produced gas reported under GHGRP to Drilling Info production data at the basin level. API notes that simplifying the approach would potentially result in a lower appearance of GHGRP coverage and an increased emission estimate.

API suggested during the expert review phase of the proposed methodology updates that,

- Data quality filters are applied in order to avoid including production data scaling where less than 6% of the gas is sold and for basins where the reported produced gas is >200% of the Drilling Info production.
- A sensitivity analysis is performed to document the impact of using a national-level approach vs.

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[11] https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2018-ghg

a basin-level approach to scale up national emissions.

It is not clear that such an analysis or data quality checks were undertaken by EPA and incorporated in the data that is presented in the public review draft GHGI. EPA should also confirm that for the current GHGI it applied the most recent GHGRP data (October 2019 GHGRP data release). For example, in the November 2019 methodology update memo for the dehydrator category does not appear to include desiccant dehydrators emissions.

Response: Additional text clarifying the development of the scale-up factor and the use of national-level versus basin-level approaches has been added to the Inventory and the memo, "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Updates to Natural Gas Gathering & Boosting Station Emissions***."[12] In the final Inventory, the most recent GHGRP data were used to calculate emissions, and an estimate for desiccant dehydrator emissions was added.***

Commenter: Colorado State University

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0018

Dan Zimmerle

Comment 6: Re: Page 3-91, lines 18-25

I recommend an explicit mention of the 'compressors/station' assumption in our methodology; since the GHGRP does not report station counts, that factor should be noted, and if possible confirmed & updated over time.

Response: Additional text was added to the Inventory to document the compressors/station assumption (see page 3-93) and to note that if data are available, this assumption will be assessed over time (see page 3-101).

Comment 7: Re: Gathering infrastructure outside of compressor station boundaries may not be included in the methodology

There is some amount of additional gathering infrastructure that is outside of compressor station boundaries, but not specifically on well pads. These sources are not included in our study, and it is uncertain if these sources were estimated in your methodology section. This should be clarified.

Response: Additional text was added to the Inventory make this clarification. See pages 3-93 to 3-95 of the report.

Comment 8: Re: Scaling factor

As in the first comment, the scaling factor (cell C75, sheet 3.6-8) of 1.075 was valid for the 2017 ratio of GHGRP gas production to DrililngInfo™ production data, but should be confirmed & updated over time.

Response: Additional text was added to the Inventory to note that the scaling factor will be updated over time if possible. See page 3-101 of the report.

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[12] https://www.epa.gov/sites/production/files/2020-04/documents/2020_ghgi_update_-_gb_stations_final.pdf

Comment 9: Re: Statement that the second largest methane source at G&B stations is "compressor venting and flaring" on page 3-83

If this is reference to our report, it should be "venting and fugitive." Perhaps our abbreviation of F&V was misunderstood. We counted flaring as a separate category, and that also appears to be consistent with the annex tables.

Response: The text in the Inventory was corrected based on the information provided by the commenter (see pages 3-93 to 3-95).

Commenter: Environmental Defense Fund, Clean Air Task Force, Apogee Economics and Policy, and The Wilderness Society

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0014

David Lyon, David McCabe, and Laura Zachary

Comment 10: Re: Natural Gas and Petroleum Systems estimates

We are concerned that the draft 2020 GHGI would deepen the Inventory's existing underestimate of natural gas and petroleum systems methane emissions, exacerbating the existing problem already present in previous editions of the inventory. While we appreciate EPA's hard work to improve the Inventory and we recognize the value in research into up-to-date emission factors for equipment used in the gathering and boosting segment of the natural gas sector, EPA should not move from emission estimates for the segment based on Marchese et al's site-wide measurements to emissions estimates based solely on Zimmerle et al's bottom-up surveys. As numerous studies have demonstrated [Alvarez et al 2018, Brandt et al 2014, and references therein], bottom-up equipment-based inventories consistently underestimate emissions from natural gas facilities for a variety of reasons.

Furthermore, the appropriateness of site-level measurements as a measure of true facility emissions was recently validated by Alvarez et al 2018, who compared site-level measurement and basin-wide measurements for 9 basins, showing excellent agreement for 7 of the 9 basins and agreement within uncertainty for all basins. In contrast, the disagreement between equipment-based survey approaches and facility-level emissions measurements has been demonstrated, as mentioned above. As described by Brandt et al 2014, there are a number of systematic reasons why equipment surveys underestimate emissions.

The impacts of the proposed changes are substantial. The recalculations to the natural gas system methods, dominated by changes to the G&B segment, resulted in an average decrease in total natural gas system methane emission estimates of 14.1 MMT CO_2 Eq., or 8 percent, across the 1990 through 2017 time series. Annual G&B station methane emission estimates decreased by an average of 36 percent in the current Inventory for the 1990 to 2017 time series, compared to the previous Inventory.

Looking specifically at methane emission estimates for 2017 further illustrates the dramatic decrease due to the proposed revisions. The combined impact of GHGI 2020 methane emissions revisions across the natural gas system to 2017, compared to the previous Inventory, is a decrease from 165.5 to 139.1 MMT CO_2 Eq. (26.5 MMT CO_2 Eq., or 16 percent). A substantial portion of that change, the revisions to the G&B segment resulted in a decrease from 55.5 to 32.0 MMT CO_2 Eq. (23.5 MMT CO_2 Eq., or 42 percent). Revisions to the G&B segment accounted for 23.5 of the 26.5 MMT CO_2 Eq. (or 88 percent) of the total decrease from the natural gas system methane emissions estimates for 2017.

For the reasons described above, EPA should not move forward with the changes to the methodology for estimating emissions from gathering and boosting outlined in the Draft Inventory.

Alvarez et al 2018 estimated that U.S. Petroleum and Natural Gas System methane emissions in 2015 were 13±2 million metric tons, approximately 60 percent higher than 2017 EPA Greenhouse Gas Inventory estimate. The study relied primarily on site-level measurement data to extrapolate emissions, which were then validated with independent, basin-level top-down estimates. For gathering stations, Alvarez et al 2018 estimated emissions based on data from Marchese et al 2015, which were based on around 100 site-level measurements and adjusted upward by around 10 percent to account for emissions from facilities above the sampled range of the log-normal distribution. EPA's proposed change to gathering station emissions would widen the discrepancy between Alvarez et al 2018 and the GHGI to around 80 percent, which is inconsistent with numerous peer-reviewed papers that have determined basin-level emission estimates are substantially higher than regional estimates derived from GHGI data or methods.

The main cause of this 80 percent discrepancy likely is large, anomalous emission rates caused by malfunctions or other abnormal events that are difficult to both quantify with component-level approaches or categorize within a traditional, source-based emission inventory - even a high-quality bottom-up inventory such as Zimmerle et al 2019. Therefore, the proposed approach would inadequately account for super-emitter emissions in the G&B sector and cause EPA's estimate to deviate further from empirically-based estimates.

We therefore do not support EPA's decision to move away from using empirical, site-level data from Marchese et al (2015) to estimate methane emissions from gathering and boosting stations. For future considerations of updates to this source, we suggest that EPA consults the EDF and CATF stakeholder feedback on the 2018 GHGI memos, describing an alternative method that uses data from both GHGRP and Marchese et al to most accurately estimate total emissions with a best approximation of source-specific emissions.

Component emission factors for 2016/2017 should not be used for historic emission years. In the proposed revisions, EPA uses Zimmerle et al 2019 calculated emission factors for compressors, tanks, acid gas removal units, combustion slip, dehydrators, yard piping, and separators across all years in the inventory time series (1990-2018). Above we suggest that EPA should not proceed with using the updated methodology as discussed in the Draft Inventory. If EPA chooses to nevertheless use this methodology, given that Zimmerle et al state that the lower nationwide emissions that result from their component emission factors (based on a 2017 survey), compared to the nationwide results from Marchese et al, may be in part due to improved technologies and industry practices implemented in the past few years, what assumptions does EPA make in applying the Zimmerle et al 2019 emission factors to revise Inventory emission estimates for 1990-2016? On what basis does EPA conclude that Zimmerle et al emission factors are representative of earlier years?

For the remaining G&B station components (station blowdowns, dehydrator vents, pneumatic devices, flare stacks, and pneumatic pumps), EPA calculates emission factors for 2016-2018 using year-specific GHGRP subpart W data. However, for 1990-2015 for those GHGRP-based components, EPA uses 2016 emission factors. Why does EPA believe that GHGRP-based emission factors for 2016 are representative of earlier years?

Response: In their paper, Zimmerle et al. discussed differences between the Zimmerle et al. study (current Inventory data source for gathering stations) and the Marchese et al. study (previous Inventory data source for gathering stations). The differences noted in Zimmerle et al. are: (1) the Zimmerle et al. study uses an updated and likely more representative mix of stations in terms of

throughput and complexity, (2) the Zimmerle et al. study accessed component level activity and emissions data from the GHGRP, which were not available at the time of the Marchese et al. study, and which represented data from a large set of operators for the entire U.S., (3) the two studies utilized different measurement methods, and (4) there may have been operational improvements to G&B stations and/or construction of new lower-emitting stations during the intervening years between studies due to increased attention to CH4 emissions across the natural gas value chain.

The Zimmerle et al. study detected a number of large emitters. For example, the study noted that "For most leaker factors, 50% or more of emissions are due to the largest 5% of emitters." The set of emission factors developed in the Zimmerle et al. study which were used to calculate emissions in the GHG Inventory include estimates for all emissions detected in the field campaign, including estimates for large emitters, and the study notes that these "Large emitter emissions have substantial impact on major equipment emission factors, adding 70% - 83% to the impacted major equipment factors."

EPA considered an approach using the Zimmerle et al. (measurements conducted in 2017) and GHGRP (data available starting in 2016) data in recent years and using from Marchese et al. (measurements from 2013 and 2014) in earlier years but did not implement it in the Inventory due to incongruencies between the studies noted above. If the Marchese et al. study in emissions and activity data were used for early years of the time series (e.g., 1990-2014) and the Zimmerle et al. and GHGRP data were used in more recent years (e.g. 2016-2017), there would be a large decrease in emissions over a short period of time due to this transition. Some fraction of the decrease would likely be attributable to improvements in technologies and industry practices. However, as noted above there are other differences between the studies such as study representativeness and the difference between the two is likely not entirely due to changes in technologies (or any other single factor). For this reason, EPA did not implement an approach that uses data from both of the studies in different parts of the time series.

Commenter: National Association of Clean Water Agencies (NACWA)

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0016

Cynthia A. Finley, Ph.D.

Comment 11: Re: wastewater treatment emissions from publicly owned treatment works (POTWs)

The wastewater treatment category includes publicly owned treatment works (POTWs), septic systems, and industrial wastewater treatment systems. NACWA's review focused on emissions from POTWs.

NACWA has submitted comments on the wastewater treatment section since the 2005 Inventory, and we appreciate the clarifications that EPA has made over the years for the emissions calculations and the factors that are used in the calculations. Several references were updated in the 2017 Inventory to better reflect current characteristics of the sector. However, more work needs to be done on updating data sources. For example, the outdated 2004 Clean Watershed Needs Survey (CWNS) was still used as the basis for the percent of wastewater flow to aerobic and anaerobic systems, the percent of utilities that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters. The forecasts made using the 2004 CWNS and previous editions of the CWNS may not accurately reflect recent trends and practices for wastewater utilities.

Another factor that should be updated is the wastewater flow of 100 gal/person/day, which was taken from a 2004 document published by the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. Due to droughts and effective water conservation measures, many areas of the US now have wastewater flows significantly less than this value. NACWA recommends that EPA consider updated wastewater flow references that represent current wastewater flow in other regions of the country.

NACWA agrees with EPA's planned improvements for the Inventory and encourages development of US-specific methodologies and emission factors when appropriate. As NACWA has explained in comments on the Inventory in previous years, the Association believes that the nitrogen loading rates for $N_2O_{EFFLUENT}$ are sourced incorrectly and that using information from the existing National Pollutant Discharge Elimination System (NPDES) database will yield more accurate and justifiable loading rates.

The NPDES permitting program represents long-term, nationwide facility performance that would allow emissions estimate projections over the time series represented in the Inventory. EPA should also investigate additional references for nitrogen loading rates.

NACWA also asks that EPA consider reformatting the explanations of the variables used to calculate methane and nitrous oxide emissions. Both the value used in the calculation and the source should be clearly stated, preferably in bullet or table form. The current paragraph format, which generally does not include the value used in calculation, increases the difficulty of reproducing the emissions calculations.

Response: EPA appreciates the commenter's feedback on the emissions estimates for POTW, and the encouragement to develop U.S.-specific methodologies and emission factors as described in the Planned Improvements within Section 7.2. Each year in compiling estimates, EPA looks for updated wastewater activity data sources and we appreciate any future suggestions provided by the commenter or others on specific data sources for wastewater flow and sources to replace the CWNS. We are aware of a voluntary survey of POTWs that is currently being administered by EPA's Office of Water that could provide valuable updated activity data depending on response rate and representativeness of facilities that reply. We ask the commenter to encourage its members to complete the survey to ensure the resulting data may be used for future Inventories.

EPA has considered the suggestion to estimate nitrogen effluent loads based on data reported under EPA's National Pollutant Discharge Elimination System (NPDES) Program. Unfortunately, very few POTWs are required to report their effluent nitrogen concentration or load, and those that do are typically required to meet more stringent limits than the average POTW. At this time, EPA is unable to confirm that these data would be representative of the entire industry. In addition, this would represent a departure from the IPCC accepted methodology and would require substantiation that it results in a more robust estimation of these nitrous oxide emissions.

EPA also appreciates the formatting suggestion and will explore ways to improve the clarity of the explanation of the variables in the emission equations and the sources for those variables in future reports.

Commenter: National Cattlemen's Beef Association

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0004

Scott Yager, Mary-Thomas Hart

Comment 12: Global Warming Potential Methodology

The Draft Inventory notes that, in 2018, enteric fermentation emissions from cattle accounted for 1.92% of all United States GHG emissions. To complete this calculation (in addition to other contribution percentage calculations in the Draft Inventory), EPA utilized the GWP100 methodology. As EPA seeks to improve its inventory, NCBA urges the Agency to forgo the GWP100 methodology, instead adopting the GWP* methodology – specifically with regard to methane emissions. Under the United Nations Framework Convention on Climate Change (UNFCCC), reporting of GHG emissions has been standardized in terms of CO_2-equivalent (CO_2-e) emissions using Global Warming Potentials (GWP) over 100 years, but the conventional GWP100 methodology does not adequately capture the different behaviors of long-lived climate pollutants (LLCPs) and short-lived climate pollutants (SLCPs). The atmospheric lifetime and radiative impacts of different GHGs differ dramatically. Acknowledgement of this reality led to the widescale adoption of the GWP100 methodology. GWP100 equates emissions using a scaling factor – CO_2-e. GHGs are assigned a GHG equivalency, then that number is used to determine the emissions' potential impact. Following GWP100, a pound of methane equates to 25 pounds of CO_2. Thus, methane is calculated as $25CO_2$e. However, this simplified scaling factor fails to recognize the amount of time emissions remain in the atmosphere – an equally important factor in determining potential atmospheric impact. The GWP* methodology seeks to remedy this oversight.[13]

Anthropogenic warming estimations are largely determined by the cumulative total emissions of LLCPs and the emission rates of SLCPs. GWP* equates an increase in the emissions rate of an SLCP with a single "pulse" emission of CO_2, and thus considers not only the initial intensity of GHGs, but also the amount of time that they remain in the atmosphere. This approach is a significant improvement on the conventional GWP100 methodology. Further, the GWP* methodology modifies the conventional GWP definition to consider CO_2 warming equivalents (CO_2-we) rather than CO_2-e. Following GWP*, SLCPs can be incorporated directly into carbon budgets consistent with long-term temperature goals, because every unit of CO_2-we emitted generates approximately the same amount of warming, whether it is emitted as a SLCP or a LLCP. This is not the case for conventionally derived CO_2-e measurements.

Response: As noted by the commenter, EPA uses 100-year Global Warming Potentials (GWP) from IPCC's Fourth Assessment Report as required in reporting annual inventories to the UNFCCC. This is required to ensure that national GHG Inventories reported by all nations are comparable. The Inventory presents estimates on a gas by gas basis to allow users to understand relative contribution across all sources of methane, see Table 2-1. The report also includes unweighted estimates in kilotons (see Table 2-2 of the Trends chapter on p. 2-4) and stakeholder/researchers can and have used these values to apply other metrics. We are also tracking the ongoing work of the IPCC in this area related to the development of their Sixth Assessment Report. EPA takes note of the supplemental materials submitted with the comments.

Comment 13: Greater Recognition of Grassland Carbon Sinks

NCBA is pleased with the Agency's effort to recognize existing GHG emission offsets. As the Agency noted in the Draft Inventory, carbon sinks account for a 20% offset of agricultural GHG emissions – significantly reducing the net impact of the industry. NCBA encourages the bolstering of this section generally, so that regulated stakeholders and consumers alike can assess the net impact of GHG emitters. Going forward, NCBA urges EPA to specifically consider the environmental benefit of managed grazing, a conservation practice implemented by ranchers across the country. It is well-known that

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[13] Cain, M., Lynch, J., Allen, M.R. et al., Improved calculation of warming-equivalent emissions for short-lived climate pollutants, Clim Atmos Sci 2, 29 (2019). https://doi.org/10.1038/s41612-019-0086-4.

rotational grazing leads to increased carbon sequestration.[14] Globally, if soil organic carbon in agricultural lands and grasslands increase 10% over the course of the 21st century, carbon dioxide concentrations in the atmosphere could be reduced by 110 ppm.[15]

Response: Improved grazing management such as rotational grazing is an activity that EPA would like to capture better within the GHG inventory but has proved to be challenging due to lack of a consistent time-series of national activity data for these alternative grazing management approaches. EPA would appreciate information on activity data sources that NCBA is aware of so these practices can be better reflected in the methods currently used to estimate emissions and removals from livestock management on grasslands.

EPA also notes that the offset percentage or "relative" sink cited by NCBA in their comments is not presented in the report. We were unable to replicate this value based on estimates in the Inventory report.

Commenter: National Lime Association

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0003

William C. Herz

Comment 14: Re: The IPCC factor used to account for lime kiln dust (LKD) CO_2 emissions

NLA notes that, as in previous years, the Draft U.S. Inventory of Greenhouse Gases and Sinks 1990 – 2018, published on February 11, 2020, still relies on the inaccurate IPCC factor of 1.02 to account for lime kiln dust (LKD) CO_2 emissions, and CO_2 emissions accounting for off-spec lime and other wastes are absent.

NLA previously submitted comments in 2013 and 2015 concerning inaccuracies on the U.S. Inventory of GHG Emissions and Sinks that recommended EPA should discontinue using the IPCC emission factors to account for LKD emissions, and also take into account CO_2 emissions from off-spec lime, scrubber sludge, and other wastes (NLA prior comments are included as an Attachment). This issue is important to NLA members not only to ensure data accuracy, but to EPA's stated goal of agreement and alignment with the GHG mandatory reporting system. Currently, EPA calcination emission calculations rely on output-based emission factors from the relatively outdated IPCC 2006 GHG Guidelines.

NLA's recommendations to adopt accurate calcination emissions calculation methodology for LKD and off-spec lime, scrubber sludge and other wastes are based not on modelled data but rather on analysis of actual production data, including accurate measurement of CaO and MgO oxide contents of lime and LKD provided to NLA from its member companies (see NLA comments 2013). These comments and supporting data should be sufficient to provide EPA with the basis to generate more accurate emissions estimates for LKD, off-spec lime and scrubber sludge.

In summary, NLA comments concluded that the IPCC's output-based approach for estimating calcination emissions from U.S. lime products is highly accurate, but **it understates emissions from LKD and other byproducts/wastes generated in the United States**. The NLA recommended that lime calcination

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[14] Wang, T.; Teague, W.R.; Park, S.C.; Bevers, S. GHG Mitigation Potential of Different Grazing Strategies in the United States Southern Great Plains. Sustainability, 7 (2015), pp. 13500-13521.

[15] Lal, R., *Sequestering carbon in soils of agro-ecosystems*. Food Policy. 36 (2011), (Suppl. 1): S33-S39.

emissions should be multiplied a factor of 1.06 (not 1.02) to account for LKD, and by 1.02 to account for wastes generated at lime plants (which are currently not accounted for).

However, in the "Uncertainty and Time-Series Consistency" section of the Draft Inventory, EPA acknowledges NLA's concern using the erroneous factor to account for LKD emissions. EPA also notes the sharing of historical emissions data and calculation methodologies between NLA and EPA, but adds it is still reviewing the information.

EPA also adds other caveats, such as uncertainty regarding the availability of data across time series needed to generate a representative country-specific LKD factor, and uncertainty associated with the reliability and completeness of voluntarily reported plant-level production data, and the need for further research and data to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on IPCC guidelines.

Further, in the "Planned Improvements" section, EPA cites limited resources and the need for additional QA for not incorporating NLA's recommendations into the current inventory report.

As previously stated, the NLA conclusions and recommendations were based on accurate NLA member data. Because EPA continues to use inaccurate IPCC's LKD generation rates, calcination emissions continue to be understated and we urge EPA to take our recommendations into consideration. Further, if as indicated, there are other supporting data we can provide that would add weight to our argument, please let us know.

In addition, we know that EPA has a strong interest in having both the GHG Inventory and the Mandatory GHG Reporting system be in agreement as much as possible. This is important not only for EPA's creditability but also for the public's and stakeholders' understanding of these issues as well.

The on-going differences NLA has outlined are significant and should be corrected.

Response: EPA appreciates NLA's comment and interest in improving emissions associated with lime kiln dust generation (LKD) and has reached out to the commenter to discuss available data to advance efforts to address this potential update.

Commenter: National Waste & Recycling Association, SCS Engineers, Solid Waste Association of North America, Republic Services, Waste Managment, Weaver Consulting Group

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0005

Jesse Maxwell

Comment 15: Degradable Organic Carbon (DOC)

We are pleased that EPA has evaluated stakeholder input regarding DOC and k values, and is developing an analysis to update default values for both DOC and k in its Greenhouse Gas Reporting Program (GHGRP) that then would be applied to the emissions estimates for MSW landfills in the GHG Inventory data for years 2005 to the present. We previously submitted comments recognizing that the default DOC value used in the GHGRP does not reflect recent trends in the composition of waste disposed in MSW landfills. Notably, in 2019, the Environmental Research and Education Foundation (EREF) published a white paper updating the DOC values for MSW landfills and revised its DOC estimate in 2020 with additional technical data to further substantiate representative DOC values for MSW. We encourage EPA to account for this recent data in its planned improvements to the GHGRP Subpart HH methodology to present more accurate emissions data from MSW landfills in the 2005 and later years of the GHG Inventory. We also offer our expertise in assisting EPA in preparing the anticipated multivariate analysis that attempts to optimize DOC and k values across our sector.

We also are encouraged by EPA's efforts to identify potential improvements to the DOC and k values for MSW landfills in the GHG Inventory for years 1990 to 2004. EREF has assembled a comprehensive list of waste characterization studies, including those evaluated by EPA, for this Inventory time series. EREF used the reliable data from those studies to reevaluate the DOC values for the years 1990 onward and in February 2020 provided EPA with its new findings to supplement EREF's 2016 white paper and its January 2019 updates. The additional data reinforces the need for updating the DOC values and should be used to inform EPA's process for updating the GHGRP as well as the GHG Inventory.

Chapter 7 of the GHG Inventory explains that EPA uses one DOC value of 0.20 to calculate emissions for the years 1990 through 2004. The GHGRP allows landfills to use 0.20 for bulk MSW or allows a landfill to further delineate waste streams by accounting for separate shipments of construction and demolition (C&D) waste, which uses a DOC of 0.08, and separate shipments of inert wastes, which may use a DOC of 0.0. If a landfill delineates in this way, it must use a DOC of 0.31 for its MSW volumes, which applies an artificially high DOC to MSW, and inappropriately overestimates emissions. The required DOC value of 0.31 fails to account for the significant volumes of C&D and inert wastes that are incorporated in MSW, and which cannot be separated from the MSW or accounted for distinctly, as can discrete shipments of inert wastes from industrial or C&D recycling facilities. Please let us know how we can assist the agency in providing additional data on DOC and k values for this Inventory time series.

As stated previously, in 2016, EREF undertook a state-based study of DOC values for both landfills receiving only MSW (MSW Only Landfills) and for Non-MSW Material going to MSW Landfills. EREF updated the 2016 paper in January 2019 and February 2020 with additional information based on new waste characterization information. The DOC guideline recommended by EPA for MSW Only Landfills is 0.31 and the recommended guideline for bulk material (combined MSW, C&D and inert waste streams) going to MSW landfills is 0.20. EREF concluded both guidelines over-estimate the amount of organic waste deposited in landfills, which results in inaccurate estimates of landfill gas generation and methane emissions. Furthermore, neither of the EPA-recommended DOC values have been reviewed in many years. It is time EPA update the DOC values for MSW and Bulk waste and we believe that the most valuable focus would be to reassess the DOC values incorporated in the GHGRP used for inventory years 2005 forward.

EREF reviewed 17 recent waste composition studies for MSW Only Landfills conducted by 13 states and confirmed that waste composition has, and continues to, change over time, as fewer organic materials are sent to MSW landfills. Since EPA cites the EREF research as a rationale for reassessing DOC values for 1990-2004, the following quotes from EREF clearly suggest that the data strongly suggest reevaluating DOC values used in the GHGRP for years 2005 and later:

> All characterization studies had DOCMSW values significantly less than the default value of 0.31, which suggests this value is not representative of real-world conditions for MSW (Table 3; Figure 4). Analysis of U.S. EPA data … also results in a significantly lower DOCMSW value compared to the U.S. EPA guideline of 0.31, with DOCMSW values ranging from 0.218 in 1994 to a minimum of 0.160 in 2015 (Figure 4; Appendix B). Both the state characterization studies and U.S. EPA Facts and Figures data independently suggest that a DOC guideline value of 0.31 for MSW is not representative of the landfilled MSW stream….
>
> The use of a single DOC value as a guideline for all U.S. landfills makes the implicit assumption that waste composition does not change over time or due to location. The results presented

> here suggest these are not valid assumptions and that, collectively, the use of a static DOC value of 0.31 may lead to inaccurate estimates of landfill gas emissions for landfills that only accept MSW. Because this specific analysis is focused only on MSW materials, one would expect the inclusion of non-MSW materials going to a landfill to impact DOC estimates even more.[16]

With respect to Non-MSW going to MSW Landfills, EREF finds "a common assumption is that all waste materials entering MSW landfills consist only of MSW materials. As noted previously, MSW Landfills rarely accept MSW exclusively. Rather, most MSW Landfills (landfills in 45 states) are authorized to accept other Subtitle D wastes in addition to MSW,"[17] and often non-MSW materials comprise a significant percentage of MSW landfills. In addition, EREF notes:

> Given that a third of incoming waste to MSW Landfills consists of non-MSW materials, there is significant potential for non-MSW materials to impact the relative fraction of organics and degradable organic carbon (DOC) of the MSW Landfill waste stream.[18]
>
> The amount and types of non-MSW Subtitle D organic wastes impact the DOC value for the landfilled waste since it consists of both MSW and non-MSW streams. This combined DOC value (DOCSubD) incorporates degradable organic carbon from all Subtitle D wastes accepted at MSW Landfills (both MSW and non-MSW) …. State waste characterization studies were used to estimate the relative fraction of each organic constituent for C&D and industrial waste … and DOC for each waste type was calculated using Equation 1b. Based on this analysis the DOCSubD value of landfilled waste is 0.167 (Table 7).[19]

EREF also highlights that the DOCSubD value:

> … is lower than the guideline value of 0.20 for bulk waste. It is also lower than the average DOCMSW value of 0.191 computed in the prior section, indicating the inclusion of non-MSW decreases overall DOC. Using the same approach as for the DOCMSW analysis, state-specific organics content and DOCSubD values for all fourteen states with sufficient data were determined and presented in Table 8, below. … The results, all for 2013, highlight differences in DOCSubD based on locale and suggest the use of a static 0.20 guideline for bulk waste may lead to inaccurate estimates of methane generation and emissions, especially in some areas.[20]

Thus, EREF concludes as follows:

> The average computed DOC value for MSW using state data was 0.191, or roughly three-fifths of the MSW guideline value. The average computed DOC value for bulk waste using state data was 0.167, or roughly four-fifths of the bulk waste guideline. This analysis suggests that the U.S. EPA's guideline DOC values of 0.31 for MSW-only landfills and 0.20 for facilities accepting non-MSW Subtitle D wastes overestimate DOC at these landfills and may result in inaccurate estimates of landfill gas generation and methane emissions.[21]

Based on this review of the DOC values for MSW landfills, the waste sector concludes that the long-standing DOC values developed in the past over-estimate both landfill gas generation and methane

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[16] The Environmental Research & Education Foundation (2019). Analysis of Waste Streams Entering MSW Landfills: Estimating DOC Values & the Impact of Non-MSW Materials., pp 8 – 9. Retrieved from www.erefdn.org

[17] Ibid., p. 10.

[18] Ibid., p. 11.

[19] Ibid., p. 13.

[20] Ibid., p. 14.

[21] Ibid., p. 15.

emissions. The data provided by EREF confirms that two trends are driving the changes in waste composition at MSW Landfills. First, many MSW landfills are handling less organic matter now, and we anticipate this trend will continue due to state and local organics diversion goals. Second, the increase of Subtitle D non-MSW waste disposed of in MSW landfills has altered the DOC for all waste deposited in MSW Landfills. EPA validates these trends in the GHG Inventory's Chapter 6 discussion of carbon sequestration of harvested wood products, yard waste and food waste, as Table 6-85 shows a significant reduction in sequestered carbon since 1990 due to reduced volumes of organic wastes disposed in landfills.

Based on EREF's research, we urge EPA to update the DOC values to reflect significant changes in the amounts and types of organic materials being landfilled over the past 20 years. The values now in use are inaccurate and should not be used going forward. We recommend that EPA review and update the DOC values for the entire 1990-2018 time series of the GHG Inventory and prioritize updates of the DOC values used in calculating GHG emissions under Subpart HH of the GHGRP.

Response: EPA appreciates the commenter's feedback on the DOC as applied to estimating methane generation and emissions from MSW landfills. We also appreciate the information provided about the most recent Environmental Research and Education Foundation (EREF) white paper. As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA is developing a multivariate analysis solving for optimized DOC and k- across the more than 1,100 landfills that report under subpart HH of the GHGRP. This analysis uses publicly available data directly reported to the GHGRP. The results of this analysis could inform updates to the default DOC and k-values used by landfills subject to reporting under subpart HH of the GHGRP in calculating their facility-level emissions. For updates to the DOC to be reflected in the Inventory, the updates also need to be incorporated in Subpart HH of the GHGRP given its direct use in estimating national-level emissions from MSW landfills.

Comment 16: The Scale-Up Factor for MSW Landfills

We find the explanation of the methodology EPA employed to arrive at the scale-up factor to be clear. We also are encouraged that EPA intends to periodically assess and revise the scale-up factor based on reasonable expectations that landfills that do not report under the GHGRP are likely to be smaller, closed sites with declining GHG emissions and that reporting landfills will continue to represent a larger proportion of waste-in-place. For example, starting in 2010, every year fewer landfills have reported more than the 25,000 $MTCO_2e$. Yet, every year, more landfills are included in the GHGRP. This means that more of the waste is covered by reporting facilities on an annual basis.

Year	# of landfills reporting	# of landfills >25k $MTCO_2e$	Total $MTCO_2e$ reported
2010	1235	975	101,920,033
2011	1240	965	93,830,839
2012	1252	961	94,375,699
2013	1278	946	91,159,615
2014	1290	941	90,817,217
2015	1294	935	89,746,871
2016	1300	914	86,905,137
2017	1304	898	86,464,158

2018	1313	896	89,215,401

Again, most landfills that are exempt from the GHGRP requirements are old, small, closed landfills. The potential methane emissions from these sites decrease year over year by approximately 3 percent, on average. Therefore, the emissions contribution from these sites will continue to decrease compared to the sites that report via the GHGRP. The scaling factor must be adjusted to reflect the declining contribution of the exempt sites.

Response: EPA appreciates the commenter's feedback on the clarity of the methodology used to develop the scale-up factor to account for landfills that do not report to the GHGRP. EPA also agrees with the commenter's feedback that the scale-up factor should be evaluated on a routine basis. There is a large amount of uncertainty associated with the number of non-reporting landfills and their total waste-in-place and the scale-up factor is our best estimate given the available information. EPA plans to reexamine the scale-up factor for the 1990-2019 Inventory cycle to determine if there are additional landfills reporting to the GHGRP such that the waste-in-place amounts for those landfills can be removed from the scale-up factor assumptions. At the same time, EPA will also account for those landfills that have stopped reporting to the program because they were able to exercise the off-ramp. Any additional information from commenters on landfills that do not report to the GHGRP that could help refine the scale-up factor assumptions are always welcome and appreciated.

Comment 17: Methane Oxidation Factor

Our previous years' comments on the methane oxidation factor used for the 1990 to 2004 Inventory time series remain unchanged and are repeated below. EPA calculates a national estimate of methane generation and emissions using a combination of secondary data sources that detail the annual quantity of waste landfilled and the annual quantity of methane recovered from facilities with landfill gas collection and control systems. EPA applies a 10% oxidation factor to all facilities for the years 1990 to 2004. This 10 percent default factor contrasts significantly with the average methane oxidation factor of 19.5 percent applied through use of GHGRP data, to the later years of the time series (2005 to 2018). Importantly, the 19.5 percent average oxidation rate incorporated in the GHGRP, subpart HH, emissions data is premised on a more detailed and up-to-date estimation approach than is the default value of 10 percent. It is also a conservative average value, as the GHGRP methodology restricted the maximum oxidation rate to 35 percent.

In its work to review and revise the method for calculating methane oxidation under subpart HH of the GHGRP, EPA acknowledged the need to update the default 10 percent oxidation value. The default value was based on only one field study, at a landfill without gas collection and control, and did not reflect the much higher oxidation values found in numerous subsequent, peer-reviewed field studies. Given the plethora of scientific studies showing methane oxidation to be several times higher than the EPA and IPCC default value,[22] we strongly recommend EPA apply a revised value (perhaps the average oxidation value from the GHGRP) to the earlier years of the time series.

Response: EPA appreciates the commenter's feedback on the oxidation factor as applied to estimating emissions from MSW landfills. EPA regularly reviews new literature related to landfill methane oxidation and investigated options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux) or the average oxidation factor across

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[22] Solid Waste Industry for Climate Solutions, 2.2 Methane Oxidation Addendum 2012, November 19, 2012.

facilities reporting to the GHGRP (approximately 19.5 percent). At this time EPA has decided not to revise the methane oxidation factor for the 1990-2004 time series since such a change will likely result in a noticeable discontinuity in the emissions between 2004 and 2005-2010 (i.e., a jump in emissions between 2004 and 2005) that would need to be investigated and resolved to ensure methodological consistency over the time series and to accurately reflect trends. We continue to advance efforts to improve the methane generation calculations in the landfills section of the Waste Chapter by focusing on improvements to the DOC and k-value per responses to other comments submitted by this commenter, in order to make best use of the available resources across the Inventory compilation process.

Comment 18: The k Factor (Methane Generation Rate Constant)

As discussed above, we are encouraged that EPA is evaluating stakeholder input on k value for both the 1990 to 2004 Inventory series and for 2005 to the present. We also are pleased that EPA is investigating k values for different climate types against new data and other landfill gas models, as well as assessing the uncertainty factor applied to these k values in the Waste Model, and we offer our support to EPA in collecting and evaluating this information. As noted in previous years' submissions, the waste sector is concerned that these k-values are outdated and rife with uncertainty, as confirmed by the *Draft AP 42.2.4 Municipal Solid Waste Landfills*, which states:

> There is a significant level of uncertainty in Equation 2 and its recommended default values for k and Lo. The recommended defaults k and Lo for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH_4 emissions that ranged from ~30 to 400% of measured values and had a relative standard deviation of 0.73 (Table 2-2). The default values for wet landfills were based on a more limited set of data and are expected to contain even greater uncertainty.[23]

The waste sector has previously highlighted the significant issues with the k values used in the *Draft AP-42 Section 2.4: Municipal Solid Waste Landfills*. In fact, EPA has never finalized AP-42 for MSW landfills, despite the k-value issues identified by EPA in both AP-42 and the Background Information Document. With uncertainties in CH_4 emissions ranging from -30% to 400% under EPA's assessment of the LandGEM model, it is difficult to rely on these data. For this reason, we support EPA's plan to review and resolve the significant problems in the k value data set. However, we also suggest that the agency review L0 value. Although an independent variable, L0 should be considered in conjunction with k value modifications because it is related to fitting the curve, where the results will be dependent on the assumptions used for the L0/DOC.

Response: EPA appreciates the commenter's feedback on the k-value as applied to estimating methane generation and emissions from MSW landfills. As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA is developing a multivariate analysis solving for optimized DOC and k-values across the more than 1,100 landfills that report under subpart HH of the GHGRP. This analysis uses publicly available data directly reported to the GHGRP. The results of this analysis could inform updates to the default DOC and k-values used by landfills subject to reporting under Subpart HH of the GHGRP in calculating their facility level emissions. As the commenter already acknowledged for updating DOC, in order for updates to the k-value to be reflected in the Inventory, the updates also need to be incorporated in Subpart HH of the GHGRP given its direct use in estimating national-level emissions from MSW landfills.

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[23] U.S. EPA, Draft AP 42.2.4: Municipal Solid Waste Landfills, October 2008, p. 2.4-6.

Comment 19: Compost Emission Factor

Our previous years' comments on compost emission factor remain unchanged and are repeated below. In ideal conditions, the composting process occurs at a moisture content of between 50 and 60%, but the moisture content of feedstocks received at composting sites varies and can range from 20% to 80%. It is common for moisture to be added to dry feedstocks prior to the start of composting to optimize the biological process. In the calculation of emissions from composting in the draft chapter, it appears that all incoming wastes were assumed to have a moisture content of 60%. If 60% is not reflective of the actual weighted average of all feedstocks, this will introduce errors in the inventory calculation that could be significant.

We recommend that the calculations be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents, or ask that further information is provided on the rationale for assuming 60% as the average moisture content of all inbound materials.

Response: EPA notes the commenter's feedback on the moisture content levels used in the calculation of emissions from composting. The calculations for composting are based on IPCC Tier 1 methodology defaults. Under this methodology, the emission factors for CH_4 and N_2O assume a moisture content of 60% in the wet waste. (IPCC 2006) EPA has included this detail to the Methodology section of Section 7.3 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018, as was done in the previous year's inventory report, so that the source of the moisture content is more transparent. In addition, EPA continues to include in the Planned Improvements section of Section 7.3 that EPA is looking into the possibility of incorporating more specific waste subcategories and category-specific moisture contents into the emissions estimates for composting in the United Stated to improve accuracy. However, to date the EPA has not been able to locate substantial information on the composition of waste at U.S. composting facilities to do so. As additional data becomes available on the composition of waste at these facilities, EPA will consider using this information to create a more detailed calculation of U.S. composting emissions.

Comment 20: Chapter 6: Land Use, Land-Use Change, and Forestry - Carbon Stocks

In Chapter 6: Land Use, Land-Use Change, and Forestry of the GHG Inventory, carbon stocks from yard trimming and food scrap in landfills are discussed starting on page 6-128. The carbon stocks are calculated according to Equation 1 on page 6-131. However, Equation 1 reduces the persistent carbon by the carbon content twice, effectively reducing the carbon storage value. The formula calculates C stock (LFC), which is the incoming weight (W) reduced by moisture content (MC), reduced by initial carbon content (ICC), reduced by degradation of the non-persistent carbon. The formula reduces stored carbon by the initial carbon content within the braces even though it had previously been accounted for. Rather the formula shown, it should be:

$LFC = W \times (1-MC) \times ICC \times \{CS + (1-CS) \times e^{-k(t-n)}\}$

Additionally, Table 6-87 shows that the decay rates for grass, leaves, branches and food scraps were 0.323, 0.185, 0.016, and 0.156, respectively. Last year's report shows the values on Table 6-81 as 0.313, 0.179, 0.015, and 0.151, respectively. It appears that the decay value for each material increased from the values shown in last year's report without any explanation. The discussion on the values references using the 2000 U.S. Census for the latest year's calculation, but the 2010 U.S. Census for the previous year's calculation. It is unclear why EPA would use the earlier census data instead of the most recent. We recommend that EPA elaborate on the changed decay rates.

The waste sector also has questions regarding Table 6-88, which shows the remaining carbon stock in landfills. Although grass has the highest decay rate and the highest moisture content, it is shown as having the highest stock in the landfill of all yard trimmings and food scraps. C stocks should represent the total carbon stored in landfills minus the amount lost from decomposition. By weight, grass should be 30 percent of yard waste, but because it is composed of 70 percent moisture, the weight is reduced by that amount. Then, only 53 percent is persistent and it has the highest decay rate and the lowest initial carbon content. Therefore, grass should have the lowest amount of C in the landfill, not the highest. It is probable that the figures for grass and branches were inadvertently switched. We recommend that EPA review the values shown in Table 6-88 to determine their accuracy.

Response: EPA thanks SWANA for their review of the Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills section of the Inventory. EPA is still evaluating the suggested changes to Equation 1 and will add this evaluation to the list of planned improvements for next year's inventory. EPA agrees with the comments related to Table 6-87 and the Census data and has corrected the table and text. EPA also agrees with the comments on Table 6-88: the table category labels were transcribed incorrectly. EPA corrected these category labels.

Commenter: POET, LLC

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0006

Kyle Gilley

Comment 21: Re: Using ethanol as a strategy to reduce GHG emissions from the transportation sector

We are troubled that over 90 percent of the carbon dioxide emissions in 2018 were associated with fossil fuel combustion, and over 35 percent of total carbon dioxide emissions are associated with the transportation sector, making the transportation sector the largest carbon emitter in the U.S. economy. See Draft Report at ES-11, ES-12. Ethanol is a renewable fuel with significant environmental and economic benefits that is an important, readily-available tool to help combat transportation sector greenhouse gas ("GHG") emissions.[24] Currently, almost all gasoline in the United States contains 10 percent ethanol; however, higher level ethanol blends--such as E15, approved for use in almost all conventional light-duty vehicles on the road today--provide additional benefits beyond E10, and are increasingly available at retail stations across the U.S.

Specifically, ethanol-blended fuels provide, at low cost, substantial GHG emissions benefits. Recent life cycle analyses show that corn starch ethanol reduces GHG emissions by approximately 40% as compared to petroleum, and additional analyses predict that these reductions may increase to 50% or more by 2022 with ongoing innovations in corn cultivation and biorefinery practices.[25] Cellulosic ethanol

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[24] As a methodological matter, we support EPA's adherence to the Intergovernmental Panel on Climate Change's guidance and the United Nations Framework Convention on Climate Change's reporting requirements to exclude biofuel estimates

[25] USDA/ICF Study, "A Life-Cycle Analysis of the Greenhouse Gas Emission From Corn-Based Ethanol," (Sep. 2018) https://www.usda.gov/oce/climate_change/mitigation_technologies/LCA_of_Corn_Ethanol_2018_ Report.pdf; Mueller, "Updated Life Cycle Greenhouse Gas Data for Corn Ethanol Production," (Mar. 2016) http://illinoisrfa.org/wp-content/uploads/2017/06/UIC-OIG-3_16_v2-1.pdf ; Michael Wang et al., Argonne National Labs, "Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Ethanol from Corn, Sugarcane, and Cellulosic Biomass for U.S. Use," (Dec. 2012) http://iopscience.iop.org/1748-9326/7/4/045905/pdf/1748-9326_7_4_045905.pdf.

provides even more substantial GHG benefits, essentially eliminating the greenhouse gas impacts of liquid fuel.[26] Ethanol plays a central role in transportation sector GHG reduction programs, such as in the California Low Carbon Fuel Standard program, in which ethanol provides over one-third of all GHG credits.[27] Without ethanol, such programs would not be able to achieve GHG reduction targets and would do so at a higher cost to consumers and regulated parties.

As a methodological matter, POET supports EPA's adherence to the Intergovernmental Panel on Climate Change's guidance and the United Nations Framework Convention on Climate Change's reporting requirements to exclude carbon dioxide emissions associated with combustion of biofuels from the Inventory totals given the biogenic nature of the fuels. See Draft Report at 3-22, n. 21. The Draft Report indicates "[n]et carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land-Use, Land-Use Change, and Forestry (see Chapter 6)." *Id*. This portion of the report does not identify any land use changes specifically associated with corn production for ethanol, and the scientific literature supports that no such relationship exists. In particular, total land acreage devoted to corn farming has remained constant since the 1930s.[28] Remarkable increases in yield have allowed farmers to meet greater demands for food and fuel using the same amount of land. Specifically, acres planted in corn have remained at or below 1930s levels while corn production has increased seven-fold.[29] Indeed, according to U.S. Department of Agriculture projections, annual corn production is anticipated to surpass 15 billion bushels by 2025 with approximately 2 million fewer acres in production.[30] Further, water usage for corn crop irrigation has decreased over time and fertilizer/pesticide use has plateaued even as corn harvest has increased substantially.[31] These modest and decreasing impacts contrast with the tremendous environmental impacts of petroleum exploration and refining, and the associated GHG emissions impacts of fossil fuel combustion.[32]

Moreover, increased use of biofuels can promote environmental and equity objectives through maximizing co-benefit improvements in local air quality for low income and vulnerable communities that have been plagued by harmful pollutants. Specifically, vehicle pollution is a key culprit of air quality issues for communities of color that breathe, on average, 66 percent more air pollution from vehicles than white residents.[33] Combustion of the fossil fuel component of gasoline and diesel results in harmful particulates and toxic aromatics like benzene and toluene.[34] Increased biofuel-blending can mitigate

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[26] *Id.*

[27] California Air Resources Board, *Data Dashboard- Figure 2 Alternative Fuels Volume and Credits*, May 15, 2019. https://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm.

[28] Ramboll, *The RFS and Ethanol Production: Lack of Proven Impacts to Land and Water* at 11 (Aug. 2019), https://growthenergy.org/wp-content/uploads/2019/09/Ramboll_RFS_Reset_Document_Final_08_18_2019.pdf.

[29] Ramboll at 11-13; K. D. Reitsma, et. al., "Does the U.S. cropland data layer provide an accurate benchmark for land-use change estimates?" AGRONOMY JOURNAL, 108(1), 266–272 (2016), https://dl.sciencesocieties.org /publications /aj/pdfs /108/1/266; J. B. Dunn, et. al., "Measured extent of agricultural expansion depends on analysis technique." BIOFUELS, BIOPROD. BIOREFINING, *11*(2), 247–257 (2017) 10.1002/bbb.1750.

[30] *Id.* at 12.

[31] *Id.* at 32.

[32] E. Parish, et. al., "Comparing Scales of Environmental Effects from Gasoline and Ethanol Production," ENVIRONMENTAL MANAGEMENT (2013) 51:3017-338 https://link.springer.com/journal/267/51/2.

[33] *Inequitable Exposure to Air Pollution from Vehicles in the Northeast and Mid-Atlantic,* UNION OF CONCERNED SCIENTISTS (June 21, 2010), https://www.ucsusa.org/resources/inequitable-exposure-air-pollution-vehicles

[34] *See e.g., New Studies Show Ethanol Reduces Emissions and Improves Air Quality*, URBAN AIR INITIATIVE (Apr. 11, 2018), https://fixourfuel.com/2018/04/11/new-studies-show-ethanol-reduces-emissions-and-improves-air-

these emissions. Biofuels' displacement of harmful fuel additives is further illustrated by a recent study conducted by the University of California Riverside (UCR), which found that greater use of ethanol-blended fuels can reduce carbon monoxide, ozone, and particulate matter levels relative to the use of gasoline-only fuels.[35] Thus, biofuel-blended fuel is positioned to ease the pollution burdens low income and vulnerable communities bear, including reducing the toxic constituents in gasoline.

Further, while other means of alternative personal transportation may be relatively expensive or require extensive infrastructure upgrades, higher biofuel blends can be utilized by nearly all consumers, and can be offered at a discounted price relative to higher GHG emitting fuels. Higher biofuel blends are a way to share the economic advantages of a low carbon transportation sector with low income consumers.

In sum, ethanol should be a key tool in the United States' strategy to reduce the GHG emissions associated with the transportation sector identified in the Draft Report.

Response: EPA thanks the commenter for the information and perspective on ethanol production and use. As mentioned, biofuel CO_2 estimates are presented in the Inventory for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations (See Section 3.11 of the Report). Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are reported in the Land Use, Land-Use Change, and Forestry sector (See Chapter 6). All non-CO_2 emissions associated with combustion for biomass energy are included in the Energy sector (See Chapter 3). Furthermore, the Inventory reports emissions in line with international conventions on country level reporting which lists emissions by source or category and not by product life cycle or fuel type. The inventory is a policy-neutral, technical report providing information on current GHG emissions and sinks and trends prepared per reporting UNFCCC Annex 1 National GHG Reporting Guidelines (see Box ES-1) and as such, it is not well-suited as a document in which to outline mitigation opportunities and goals.

Commenter: Private Citizen

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0013

Bridget Chadwick

Comment 22: Re: spelling out carbon instead of using atomic symbol "C"

Spelling out carbon instead of using the atomic symbol "C" will help readers in a search for discussions about "carbon intensity" and the "carbon content" of fossil fuels consumed.

Response: EPA appreciates the comment on improving the usability and readability of the annual Inventory report. Some instances of the use of the atomic symbol "C" were modified for this report but EPA will continue to look for ways to improve readability in future reports.

Comment 23: Re: Using the unit exajoules to describe the carbon content of petroleum products on page 3-34

For consistency with the discussion of the "carbon content" of fossil fuels and "carbon intensity" of energy, elsewhere in the Inventory, the units: MMT CO_2 eq. / QBtu should be used.

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quality/; S. Mueller, et. al., *The Impact of Higher Ethanol Blend Levels on Vehicle Emissions in 5 Global Cities*, UNI. OF ILLINOIS AT CHICAGO (Nov. 2018), http://www.erc.uic.edu/assets/pdf/UIC5cities_HEALTH_Nov12_ Final.pdf.

[35] University of California CE-CERT, *Impacts of Aromatics and Ethanol Content on Exhaust Emissions from Gasoline Direct Injection (GDI) Vehicles* (April 2018).

Response: The reference to exajoules was replaced with QBtu in the final report.

Comment 24: Re: Referring readers to Table A-41 in Annex 2.1 for "more detail on the C Content Coefficient of different fossil fuels

Table A-42 should be referenced.

Response: The reference was updated for the final report.

Comment 25: Re: The explanation of how CO_2 emissions are estimated on page 3-32

This explanation should say that the carbon content coefficients are multiplied by the molecular-to-atomic weight ratio of CO_2 to carbon i.e. 44/12, as done in the Annexes on page A-465.

Response: The explanation was updated in the Final Report to reference the molecular-to-atomic weight ratio.

Comment 26: Re: Box 3-5
This box provides a discussion of fossil fuel carbon content "ranging from about 53 MMT CO_2 Eq./QBtu for natural gas to upwards of 95 MMT CO_2/QBtu for coal and petroleum coke". A short description of the energy/CO_2 tables, A-11 to A-39, provided in the Annexes with a table of the average CO_2 emission factors of fossil fuels consumed in 2018 (coal 95.6; oil products 72.4 and natural gas 52.9 MMTCO$_2$/QBtu) would help readers understand the relationship between CO_2 emissions [MMTCO$_2$], energy consumption [QBtu] and the carbon intensity of the fossil fuel energy consumed [MMTCO$_2$/QBtu].

Response: The text box was modified in the Final Report (box 3-4) to include a reference to Tables A-42 and A-43 in Annex 2.1 for carbon contents of all fuels.

Comment 27: Re: Figure 3-16 on page 3-34

The key driver "energy consumption" should be shown in this figure.

Response: Energy consumption was not added to Figure 3-16 but was included on Figure 2-15 in the Final Report to be consistent with information provided in Table 2-14.

Comment 28: Re: Table A-44
In this table, total electricity consumption for 2018 should be corrected to 4004 billion kWh as provided in the reference document, the EIA Monthly Energy Review, November 2019.

Response: The values in Table A-44 are consistent with prior versions of the EIA Monthly Energy Review but will be reviewed for future reports and incorporate any updates to EIA data.

Commenter: Private Citizen

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0015

Jeff Moeller

Comment 29: Re: Section 7.2 Wastewater Treatment:

The calculation does not appear to include emissions that may occur in wastewater collection systems. Wastewater collection systems may be a significant source of emissions, but it may also be quite difficult to estimate these emissions. I’d recommend noting that collection systems may be another source of emissions and that more work may be needed on this topic in the future.

Response: As stated in the Planned Improvements within section 7.2 of the Inventory report, although there are insufficient data to capture emissions from collection systems, EPA plans to update emission factors for centralized aerobic treatment based on the recently published 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories. The revised emission factors account for incoming dissolved methane that is formed in the collection system and liberated during aerobic treatment.

Commenter: Private Citizen

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0002

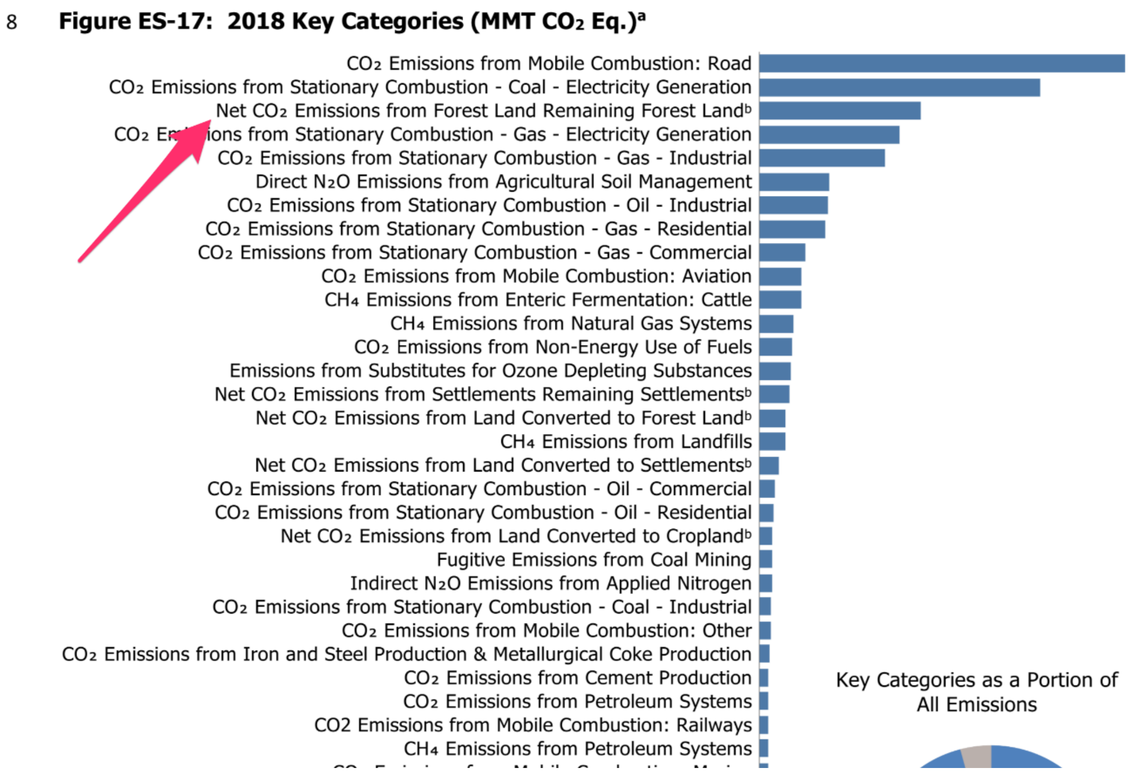
Oleksandr Stubailo

Comment 30: Re: Figures ES-17 on page ES-30 of the Executive Summary

This figure attempts to provide an overview of the key categories of emissions, but combines categories that have net positive and net negative carbon emissions in one chart.

When I was looking at the chart, I didn't initially see that categories like "Net CO_2 Emissions from Forest Land Remaining Forest Land" represented a negative impact on carbon emissions, since they were displayed in a similar way to categories with positive impact.

I'd propose displaying those categories in some other way, perhaps by making the bar in the chart a different color -- maybe green instead of blue.



8 **Figure ES-17: 2018 Key Categories (MMT CO_2 Eq.)[a]**

Response: Figure ES-17 has been updated to differentiate key categories from the LULUCF sector that have a net negative emissions. See p. ES-29 of the report.

Commenter: University of Michigan

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0017

Eric Kort, Alan Gorchov Negron

Comment 31: Re: The treatment of emissions from the offshore oil and gas sectors (pg. 3-76 to 3-77 and 3-93 to 3-94)

Regarding the update to activity data (platform counts): This represents a clear and major improvement over the prior inventory, and addresses both the previous gap in accounting for state water platforms and temporal trends.

Regarding the new method for calculating emission factors: We suggest further clarifying differences in both how emission factors are calculated (including the data sources used) and activity data that is used. Specifically noting (perhaps in a table form) this information for the different regions (Federal and State waters in Gulf of Mexico, offshore CA, offshore AK) as well as different categories (major/minor) would be very helpful.

Regarding upcoming relevant data: We have conducted a recent aerial survey of offshore oil and gas platform emissions, and have future surveys planned. In these studies emissions from offshore facilities are characterized and evaluation of different inventory estimates and methods will be provided. As this work appears in the peer-reviewed literature it will provide additional information to assess and improve reported offshore emissions.

Response: Additional information on the calculation of emission factors is included in the memo, "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Updates for Offshore Production Emissions***."[36] The upcoming availability of data relevant to offshore oil and gas emissions was noted in the Planned Improvements text for Petroleum and Natural Gas Systems. See pages 3-82 and 3-101 of the report.***

Commenter: Water Environment Federation

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0008

Patrick Dube

Comment 32: Re: References to sewage sludge

In agreement with the EPA's definition of biosolids, "Biosolids are treated sewage sludge",[37] WEF believes the term "treated" should be included when referencing sewage sludge throughout the document. For reference, this occurs on: Page 5-25, Line 29, Page 5-28, Table 5-18, Page 5-34, Line 4, Page 5-34, Line 22, Page 5-35, Line 16, Page 5-39, Line 24, Page 5-39, Line 26, Page 5-39, Footnote 20, Page 5-40, Line 41, Page 5-40, Line 44, Page 5-42, Line 1, Page 5-43, Table 5-20, Page 6-53, Line 15, Page 6-75, Line 22, Page 6-76, Line 25, Page 6-76, Line 28, Page 6-77, Table 6-40, and Page 6-124, Line 39.

Response: The text has been updated to reflect this clarification.

Other Comments

EPA received two additional anonymous technical public comment as part of the public review of the draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018. The comments can be found on the public docket and is copied below.

Commenter: Anonymous

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0007

Comment 33: Re: Detailed analysis for transportation sector emissions

In Section 2.2 (Emissions by Economic Sector) Table 2-13 and the preceding text provide detail on transportation-related emissions by various modes with electricity-related emissions distributed to the transportation sector. It would be useful to add the same type of detail for the analysis without distribution of electricity-related emissions (i.e., additionally provide the transportation-related detail that would sum to the transportation sector emissions in Table 2-10).

Response: A more detailed break-down of CO_2 emissions from fossil fuel combustion in the Transportation sector is provided by fuel type (including electricity) and transportation mode in Chapter 3 Table 3-13, with additional detail provided in Annex 3.

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[36] https://www.epa.gov/sites/production/files/2020-04/documents/2020_ghgi_update_-_offshore_production_final.pdf

[37] https://www.epa.gov/biosolids/frequent-questions-about-biosolids

Commenter: Anonymous

EPA Docket ID No.: EPA-HQ-OAR-2019-0706-0011

Comment 34: Re: Estimated costs for Greenhouse Gas Sinks by cost/MMT reduced for the various types of measures available

There should be estimated costs for Greenhouse Gas Sinks by cost/MMT reduced for the various types of measures available, ranging from additional trees, to electric car conversion, to nuclear power or gas power plants replacing coal, so that prioritized measures to reduce greenhouse gases can be understood and implemented at the lowest marginal cost.

As the 2017 report noted, the decrease in total greenhouse gas emissions between 2016 and 2017 was driven in part by a decrease in CO_2 emissions from fossil fuel combustion. The decrease in CO_2 emissions from fossil fuel combustion was a result of multiple factors, including a continued shift from coal to natural gas and increased use of renewable energy ithe electric power sectors, and milder weather that contributed to less overall electricity use. This is shown in ES-4 Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2017.

It is important, especially where GHG emissions are growing annually, to begin to or accelerate abatement procedures, including replacement of industrial or chemical processes which produce for example Carbon Dioxide or high impact hydrocarbons, by prioritizng those cost measures which produce the most emissions impact reduction per dollar expended.

Moreover, the costs of reducing GHG should be at a minimum the cost of carbon offsets in any carbon offset trading market.

If the highest 75% of GHG abatement techniques cost $50 per ton, or $75 per ton, then that should be the cost of any carbon emissions.

The United States could reduce GHG emissions in 2030 by 3.0 to 4.5 gigatons of CO2e using tested approaches and high-potential emerging technologies. These reductions would involve pursuing a wide array of abatement options with marginal costs less than $50 per ton, with the average net cost to the economy being far lower if the nation can capture sizable gains from energy efficiency. Achieving these reductions at the lowest cost to the economy, however, will require strong, coordinated, economy-wide action that begins in the near future.

Response: The inventory is a policy-neutral, technical report providing information on current GHG emissions and sinks and trends prepared per reporting UNFCCC Annex 1 National GHG Reporting Guidelines (see Box ES-1) and as such, it is not well-suited as a document in which to outline mitigation opportunities and goals. For more information on assessing implications of mitigation measures please see EPA's technical report titled *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation Potential: 2015-2050* ***at this link:*** https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases. ***See also the latest global analysis by IPCC Working Group III report published here:*** https://www.ipcc.ch/report/ar5/wg3//***, noting the development of their Sixth Assessment Report including mitigation is ongoing and anticipated to be published in 2021.***

United States
Environmental Protection
Agency

Summary of Expert Review Comments and Responses:
Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018*

May 2020
U.S. Environmental Protection Agency
Office of Atmospheric Programs
Washington, D.C.

Responses to Comments Received during the Expert Review Period on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018*

Preface

EPA thanks all commenters for their interest and feedback on the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks. To continue to improve the estimates in the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks, EPA distributed draft chapters of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* for a preliminary Expert Review of estimates and methodological updates prior to release for Public Review. The Expert Review was 30 days by sector and EPA provided experts charge questions to focus review on methodological refinements and other areas needing a more in-depth review by experts. The goal of the Expert Review is to provide an objective review of the Inventory to ensure that the final Inventory estimates, and document reflect sound technical information and analysis.

EPA received 40 unique comments on as part of the Expert Review process. The verbatim text of each comment extracted from the original comment letters is included in this document, arranged by sectoral chapters. EPA's responses to comments are provided immediately following each comment excerpt. The list of reviewers, dates of review and all charge questions distributed to reviewers are included in the appendices to this document.

Chapter 3. Energy

Comment 1: Clarity and transparency of the Energy chapter
Overall, the data is conveyed clearly and concisely. The chapter could use further explanation regarding causes of trends or changes over time.

Response: EPA thanks the commenter for the review of the energy chapter of the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks. In terms of explanation regarding causes of trends or changes over time, Chapter 2 of the National Inventory Report (NIR), not included as part of Expert Review, includes a discussion of recent trends in emissions. Chapter 2 is included in the draft report published for a 30-day Public Review, but we may consider adding some trend context to the guidance memo in future reviews to facilitate review. Section 2.1 has a discussion of recent trends in energy emissions including CO_2 emissions from fossil fuel combustion. Section 2.2 highlights trends by economic sector including with emissions from electricity distributed to economic end-use sectors. The trends discussion in the energy chapter of the NIR (Page 3-8 of the Public Review draft report) has a similar discussion to what is in Chapter 2 and EPA can look into simplifying / improving the discussion across the different chapters for future reports.

Comment 2: Description of N_2O and CH_4 emission factors
It is worth including a concise description of emissions factors in the body of the chapter for N_2O and CH_4.

Response: Annex 3.1 of the NIR includes a complete description of the methodology for estimating CH_4 and N_2O emissions from stationary combustion, and Annex 3.2 includes the discussion for mobile combustion. The methodology discussion in the energy chapter for CH_4 and N_2O emissions does include a brief description of the factors used. However, due to the technology-dependent nature of the factors and the complexity involved, especially across different model years and vehicle types for mobile sources, the details on emission factors are presented in the annex for ease of readability of the main report.

Comment 3: CH_4 leakage
Is CH_4 leakage addressed elsewhere?

Response: Fugitive CH_4 emissions from coal mining are presented in Sections 3.4 and 3.5 of the NIR. Fugitive CH_4 emissions from petroleum systems are presented in Section 3.6, fugitive CH_4 emissions from natural gas systems are presented in Section 3.7 and fugitive CH_4 emissions from abandoned oil and gas wells are presented in Section 3.8 of the NIR.

Comment 4: Increased natural gas use
3-4 (5-20): The chapter claims that natural gas use increased for residential and commercial sectors, but that only explains about half of overall natural gas increase. The power sector had a substantial increase of about 15%, a 74 MMT CO_2 increase from natural gas and a 56 MMT CO_2 decrease for coal in the power sector. This is better addressed after the tables in lines 5-20.

Response: The EPA agrees with the comment and the language in the text has been modified to indicate that the increase in the residential and commercial sectors is total energy use not just direct natural gas use. This includes increased electricity use, which leads to more emissions from electricity production in the power sector.

Comment 5: Weather impacts on heating and cooling
3-5 (4-11): Was the weather that caused more heating and cooling an anomaly? Trend? Regression to mean (after two mild summer/winters). This is well addressed in Figure 3-6 on page 3-5, and could be stated in the text.

Response: EPA agrees with the comment and the text discussing the 2018 heating degree days was modified to clarify that even though 2018 HHD were higher than in 2017 they were still 5.7 percent below normal. Figure 3-6 was also updated to clarify the derivations from normal.

Comment 6: Transportation share of power use
3-7 (19): How is transportation's share of power use so high? It is similar to the combined power of residential and commercial.

Response: Table 3-8 in the Expert Review draft (pg 3-7) of the NIR includes both direct emissions and emissions from electricity use distributed to the end-use sectors shown, including transportation. The transportation emissions are high because of emissions related to direct energy use. Table 2-12 of the NIR shows the emissions by end-use sector broken out in terms of direct energy use and electricity-related energy use. The table shows that electricity-related emissions from the transportation end-use sector are small.

Comment 7: CH_4 emissions
3-8 (7): If CH_4 emissions are from incomplete combustion / leakage, we should specify. If it's calculated through a bottom-up calculation, we should specify.

Response: More information on CH_4 and N_2O calculations are provided starting on page 3-20 of the Expert Review draft. Furthermore, Annex 3.1 of the NIR includes a complete description of the methodology for estimating CH_4 and N_2O emissions from stationary combustion. The emissions are for only the combustion component of fuel use and represent for the most part incomplete combustion emissions. The calculations are based on an approach of fuel use by combustion technology multiplied by emission factors for that fuel and combustion technology type.

Comment 8: Carbon content of natural gas versus coal
3-10 (20): It is worth adding the approximate carbon content per kWh of natural gas versus coal to explain the impact of transitioning to natural gas.

Response: Page 3-3 of the Expert Review draft includes more information on the carbon content of different fuels, which helps explain the impact on emissions of transitioning from coal to natural gas.

Comment 9: Emissions direction confusion
3-11 (1-8): These lines are confusing; the text suggests there was both an increase and decrease in emissions over timeframe.

Response: EPA agrees with the comment and the text indicating there was a decrease in emissions has been deleted. Emissions from the electric power sector increased from 2017 to 2018.

Comment 10: Increase in CO_2 emissions with respect to cooling and heating degree days
3-13: In Figure 3-11, what explains the increase of residential and commercial CO_2 emissions with respect to cooling and heating degree days between 1997 and 2011?

Response: Figure 3-11 is not meant to highlight long-term trends in residential and commercial energy use and emissions, but rather highlight how some of the annual fluctuations are tied to heating degree day (HDD) and cooling degree day (CDD) changes. To understand the type of trends identified in the question concerning increase in emissions with respect to HDD and CDD between 1997 and 2011 would require a further understanding of energy end use requirements over time. Emissions are generally tied to total energy use and are impacted by building energy efficiency, building stocks, types of energy use and GHG intensity of energy sources. That type of analysis is beyond the scope of the National Inventory Report.

Comment 11: Developing estimates of EV energy use

I have no major comments except for the need to develop bottom-up estimates of energy consumption and GHG emissions from on-road electric vehicles for inclusion in end-use sector values (as well as the table traditionally at the end of Chapter 2 summarizing Transportation-Related GHG Emissions). Proposed methods and data have been outlined in an Argonne National Laboratory Report, Impacts of Electrification of Light-Duty Vehicles in the United States, 2010-2017, available at https://publications.anl.gov/anlpubs/2018/01/141595.pdf.

Response: EPA agrees with the comment and energy use and emissions associated with electric vehicle use has been incorporated into the NIR for the transportation electricity end-use sector. The approach is generally consistent with the Argonne report and is outlined in the memo: Browning, L. (2018a). Updated Methodology for Estimating Electricity Use from Highway Plug-In Electric Vehicles. Technical Memo, October 2018.

3.1 Fossil Fuel Combustion: CO_2 from Fossil Fuel Combustion

Comment 12: Clarity and Transparency of CO_2 from Fossil Fuel Combustion Discussion
The methodology is thoroughly explained. If the carbon intensity of different energy sources themselves have changed much over time, it is worth including in Box 3-5 on page 3-17.

Response: The carbon intensity of fossil fuels themselves do not vary that much over time as is further described in Annex 2 of the NIR.

Comment 13: Data Source for Energy Use of U.S. Territories
We're not sure of any other data sources that could be used.

Response: EPA appreciates the response and continues to investigate other data sources of U.S. territory energy use.

Comment 14: GHGRP facility-level combustion emissions data
This data still needs to be updated.

Response: EPA appreciates the response and the GHGRP data has been updated for the Inventory final report. EPA continues to review the use of GHGRP data as discussed in Box 3-4 of the NIR.

3.2 Fossil Fuel Combustion: CH_4 and N_2O from Stationary Combustion

Comment 15: CH_4 and N_2O emission factors for the electric power sector
The CH_4 and N_2O emission factors for the electric power sector are based on a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. For all other stationary sectors, the emission factors used in Tier 1 methods are primarily taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Are there other more U.S.-specific CH_4 and N_2O emission factor data sources that could be utilized, especially for natural gas combustion sources?

On Line 5 of 3-14, the text states that CO_2 is estimated in line with Tier 2 methodology. This seems to contradict the first sentence of the question above.

Response: The first sentence in the question above is referencing a Tier 1 methodology used for non-electric power CH_4 and N_2O sources. Line 5 of page 3-14 of the expert review draft is referencing CO_2 emissions (not CH_4 and N_2O) and CO_2 emission estimates for all sources use a Tier 2 approach.

3.2 Fossil Fuel Combustion: CH_4 and N_2O from Mobile Combustion

Comment 16: Update to CH_4 and N_2O factors
The proposed approach of estimating CH_4 and N_2O mobile source EFs directly from annual certification data seems to be a step forward from the current regression-based approach. EPA is commended for this update and improvement.

Response: EPA appreciates the comment and continues to look for ways to improve the accuracy of emission factors used in the analysis.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels

Comment 17: Clarity and transparency of CO_2 from Fossil Fuel Combustion discussion
Stored carbon versus released carbon in non-energy products is well explained in the section.

Response: EPA appreciates the comment and continues to investigate ways to improve the transparency and clarity of the NEU discussion in the NIR.

Comments on gasoline C factor update memo

Comment 18: Speciated gasoline component data
EPA is commended for developing a new method for estimating this EF, particularly in light of the unavailability of NIPER gasoline composition data since 2009. The proposed approach seems to make sense in concept, although it is not clear if the API data can be used to speciate gasoline components or represent changes in gasoline speciation over time.

Response: EPA appreciates the comment and has identified additional data and methodologies relevant to this gasoline C factor update. EPA is still reviewing the additional data and possible approaches and therefore the gasoline C factor was not updated in this year's final inventory report. EPA is still considering the update for future Inventory cycles and data will be recalculated as needed if factors change.

Comment 19: Speciated gasoline data
EPA's use of the gasoline speciation data collected in conjunction with the API 2010 E10 blending study is supported. It should be recognized that the fuels evaluated as part of the API study are representative of the 2008-2009 timeframe. Ideally, it would be better to generate data from a new or more current nationwide study of the ultra-low sulfur gasoline/BOBs now being used to make E10, but such data are not available, so the API 2010 study is the best alternative. The use of surrogate compounds to represent or estimate the carbon content of different components of US motor gasoline fuels is not recommended.

Response: EPA appreciates the comment and has identified additional data and methodologies relevant to this gasoline C factor update that could be more relevant over time. EPA agrees that use of surrogate compounds to represent gasoline components is not advisable and is considering alternate methods beyond what was outlined in the expert review memo. EPA is still reviewing the additional data and possible approaches and therefore the gasoline C factor was not updated in this year's final inventory report. EPA is still considering the update for future Inventory cycles and data will be recalculated as needed if factors change.

Comment 20: Use of speciation data
The approach outlined in Annex 2 of the expert review memo to develop the speciated gasoline components is generally supported. However, in the Annex, EPA indicated that it picked 2 gasolines from the data supplied by API which it deemed to be representative of winter and summer gasoline fuels. It would have been useful to do a sensitivity analysis of the results based on fuels from the API data set that represented a range of summer gasoline compositions and a range of winter gasoline compositions.

Response: EPA appreciates the comment and has identified additional data and methodologies relevant to this gasoline C factor update that could be used to represent gasoline components and is considering alternate methods beyond what was outlined in the expert review memo. EPA is still reviewing the additional data and possible approaches and therefore the gasoline C factor was not updated in this year's final inventory report. EPA is still considering the update for future Inventory cycles and data will be recalculated as needed if factors change.

Comment 21: Use of EPA Trends Report
The proposed use of the EPA Trends data is an improvement over the status quo. However, it is not clear when the EPA Trends report will be updated. Data on the regular gasoline surveys that was used to produce the Trends data is available on an ongoing basis online at https://www.epa.gov/fuels-registration-reporting-and-compliance-help/public-data-gasoline-programs under the heading "Gasoline Batch Report Data." This data seems likely to be more current than the Trends report.

Response: EPA agrees with the comment that the gasoline batch data is more up to date than the EPA trends report data and will consider that as a source of information for updating the gasoline C factor. Furthermore, EPA has identified additional data and methodologies relevant to this gasoline C factor update. EPA is still reviewing the additional data and possible approaches and therefore the gasoline C factor was not updated in this year's final inventory report. EPA is still considering the update for future Inventory cycles and data will be recalculated as needed if factors change.

Comment 22: Use of EPA Trends Data
The EPA Trends data provide an adequate basis for evaluating and estimating historical changes in the composition of motor gasoline during the 1990 to 2018 time period. In the interest of maintaining data consistency, the use of the EPA Trends data is supported for the full time series under evaluation, not just for years where the NIPER data are not available. There are other sources of data available that EPA could use to "spot check" the patterns observed in the EPA Trends data. The twice-yearly survey of North American motor gasoline properties that has been conducted by the Alliance of Automobile Manufacturers (AAM) for over 20 years is one such example.[1] However, the results of the AAM survey are not freely available to the public.

Response: EPA appreciates the comment concerning the trends data and has identified a source of the data that is more up to date than the EPA trends report referenced in the expert review memo and will consider that as a source of information for updating the gasoline C factor. EPA also appreciates the reference to the AAM survey as a potential source of gasoline composition data. Furthermore, EPA has identified additional data and methodologies relevant to this gasoline C factor update. EPA is still reviewing the additional data and possible approaches and therefore the gasoline C factor was not updated in this year's final inventory report. EPA is still considering the update for future Inventory cycles and data will be recalculated as needed if factors change.

Chapter 4. IPPU

4.16 Phosphoric Acid Production

Comment 23: Phosphoric acide production facility locations
On line 12 of page 4-29, Texas and Louisiana can be removed from the list of states with facilities that use imported phosphate rock for phosphoric acide production. Plants in Texas and Louisiana have been closed permanently.

Response: EPA agrees with this suggested update and has reflected this change in the Final Inventory report.

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[1] https://autoalliance.org/energy-environment/fuel-publications/

Comment 24: Phosphate rock used to manufacture elemental phosphorous and other phosphorous- based chemicals

On line 18 of page 4-31, the text indicates that 7 percent of domestically-produced phosphate rock is used to manufacture elemental phosphorous and other phosphorous-based chemicals, rather than phosphoric acid. This percentage was less than 5 percent in 2017.

Response: EPA appreciates this clarification and has updated the uncertainty and time series consistency discussion to reflect this information in the Final Inventory report.

Chapter 5. Agriculture

5.2 Manure Management

Comment 25: B_0 values for waste characteristics data
Based on a meta-analysis and some newer literature it seems that the values in Table A-185 on page A-37 may need to be adjusted and perhaps having B_0 value for each species may not be appropriate. For example, values for the liquid fraction of dairy manure and dairy lagoon have B_0 closer to 0.5 which may help explain some discrepancies found comparing on-farm data to estimated data, see discussion below.

Reference	species	methane (m3/kg vs)	HRT (days)	temp	storage type	method
Habtewold et al., 2017	dairy liquid	0.268	160		tank	
Rosenberg and Kornelium, 2017	beef cattle	0.24	40			
Miranda et al.	dairy cattle	0.4 - 0.44			lagoon	
Rico et al	dairy cattle	0.258	90	35	solid fraction	batch reactor lab
Rico et al	dairy cattle	0.307			manure	batch reactor lab
Rico et al	dairy cattle	0.371	45		screened manure	batch reactor lab
Rico et al	dairy cattle	0.604			liquid fraction	batch reactor lab
Rico et al	dairy cattle	0.58			liquid fraction	batch reactor lab

Emissions from Anaerobic Lagoons

Recent research has suggested that methane (CH_4) emissions from liquid manure storage may be greater than is estimated using current USEPA (which follows IPCC) methodology (Wolf et al., 2017; Leytem et al., 2017 Balde et al., 2016; Owens and Silver, 2015; Lory et al., 2010). These discrepancies are likely due to several factors related to management and the factors used in the emissions calculations. The simplified equation used to estimate CH_4 generation from anaerobic lagoons is as follows:

$CH_4 = VS \times B_0 \times MCF \times 0.67 \times MDP^*$
*MDP is used in the USEPA equation not the IPCC

Where CH_4 is the emissions in kg month-1, volatile solids (VS) is the amount of VS entering the lagoon (kg), B_0 is the maximum CH_4 producing capacity of the manure (m^3 CH_4 kg VS-1), MCF is the methane conversion factor, 0.67 is the density of CH_4 at 25° C (kg CH4 m-3 CH4), and the MDP is the management and design practices factor utilized by USEPA (0.8). Comparison of on-farm emissions vs. CH_4 estimation utilizing these equations has found that emissions from liquid storage (anaerobic lagoon and tanks storage) are almost double what is estimated using this equation. Emissions estimates are close to those measured on farm in peak summer, but underestimate emissions during the remainder of the year.

There are several factors that could account for these large discrepancies between estimated and measured emissions. The inventories assume that all the liquid is going into a lagoon unless there is mechanical separation in which case that manure VS content is removed from the estimation. On many dairies, the use of earthen settling basins is common, where manure flows through the basin to settle solids before reaching the main lagoon. The settling basins behave differently than the main lagoons and in effect, in many cases, act like small digesters producing large amounts of CH_4 (Leytem et al., 2017; Arndt et al., 2018) yet due to the complexity of the liquid handling systems these are not accounted for in inventory methods. The inventory method also assumes a complete cleanout of the lagoon systems each fall. In many anaerobic lagoons, most of the water is pumped out during the year, however, sludge at the bottom may not be removed in many cases. In addition, the settling basins may be cleaned out very infrequently. Therefore, there is likely unaccounted VS remaining in the system that are available for breakdown over time as well as serving as a constant inoculum, which maintains high levels of CH_4 generation even after the lagoons are pumped out. A lag phase in CH_4 emissions of up to 50 d has been noted in the literature when manure is stored in clean tanks after which CH_4 emissions increase exponentially (VanderZaag et al. 2010a). However, modifying the estimation equation to try and account for VS carryover did not fully account for the discrepancy in CH4 emissions (Leytem and Arndt personal communication).

When one uses the monthly timestep equation for estimating monthly CH_4 emissions per Mangino et al. (2001), the emissions curve follows a trend that would be expected for a batch reactor with low emissions early in the year then spiking in the summer and then falling again to very low emissions rates in fall and winter. However, on farm research has indicated that emissions from anaerobic lagoon systems has less of a fluctuation in emissions, trending seasonally with temperature, but maintaining higher rates of CH_4 production in spring and fall than indicated using the Magino et al., method. This suggests that the emissions factors used (B_0 or MCF) may underestimate emissions. The B_0 values used in the USEPA (IPCC) emissions estimates were derived from research on the biological activity of CH_4 digesters (Bryant et al., 1976; Morris, 1976; Hashimoto et al., 1981; Hashimoto, 1983) which may not be representative of anaerobic lagoons. The broader microbial community, longer VS residence times, and lower loading rates of uncovered anaerobic lagoons may lead to higher VS degradation rates than those found in anaerobic digesters (Lory et al., 2010). According to a review of the literature, Lory et al. (2010) surmised that a properly operating uncovered anaerobic lagoon can break down solids to a higher degree than is predicted using anaerobic digester models. Therefore, B_0 may underestimate the potential amount of CH_4 generated from these lagoons and therefore underestimate overall CH_4 emissions. Based on their literature search, they reported VS degradation rates of 0.45 to 0.72 kg kg-1 VS added for dairy cows and up to 0.88 for swine. The MCF values may also underestimate emissions. The MCF is strongly influenced by temperature and assumes very little CH_4 production during colder times of the year which may underestimate emissions from anaerobic lagoons, particularly in colder climates. Another factor to consider is the amount of degraded VS that is converted to CH_4 which has also been shown to vary with literature reports ranging from 0.45 to 0.85 m3 kg-1 VS destroyed (Lory et al., 2010). Craggs et al. (2008), also reported a VS removal rate of 59% from an anaerobic dairy lagoon in New Zealand and a biogas production rate of 0.44 (m3 kg-1 VS removed), which is very similar to those estimated by Lory et al. (2010). Therefore, Lory et al., (2010) proposed an alternative estimation method:

$CH_4 = VS \times VSDF \times B' \times 0.662$

Where CH_4 is the emissions in kg year-1, VS is the total volatile solids excreted that is going to the lagoon (kg), VSDF is the fraction of VS broken down in storage (kg VS destroyed kg-1 VS added; 0.57), B' is the volume of CH_4 generated on a VS destroyed basis for the lagoon (m3 CH_4 kg-1 VS destroyed; 0.45 – 0.85), and 0.662 is the density of CH_4 at 25° C (kg CH4 m-3 CH_4). This estimation equation worked well for an anaerobic dairy lagoon in Idaho, USA (measured on farm = 14,594 kg CH_4 yr-1 vs. estimated 10,495 – 19,824) however this is only one comparison.

It appears as if the current equation for estimating emissions from anaerobic lagoons needs to be updated, however, determining the appropriate factor to change is difficult. One could increase the MCF, however in many cases it may need to be greater than 100% to account for on-farm emissions. The alternative is to increase B_0, recognizing that anaerobic lagoons are more likely to break down more VS, therefore generating more CH_4, than is estimated using the current value. A value of B_0 close to 0.50 may be more representative (for dairy) than the current value of 0.24. However, there still remains a very limited on farm dataset for validating alterations in the equations.

Response: See response to Comment 30.

Comment 26: Estimated volatile solids (VS) and total nitrogen excreted (Nex) production rates by state for cattle (other than calves) and American bison

The values in Table A-187 on page A-40 look a bit high. For example, VS for dairy cattle for Idaho are listed at 2,920 kg/animal/yr. If I use the ASABE 2005 values, this would be 2,582 or if I used the current IPCC default value it would be 2,037.

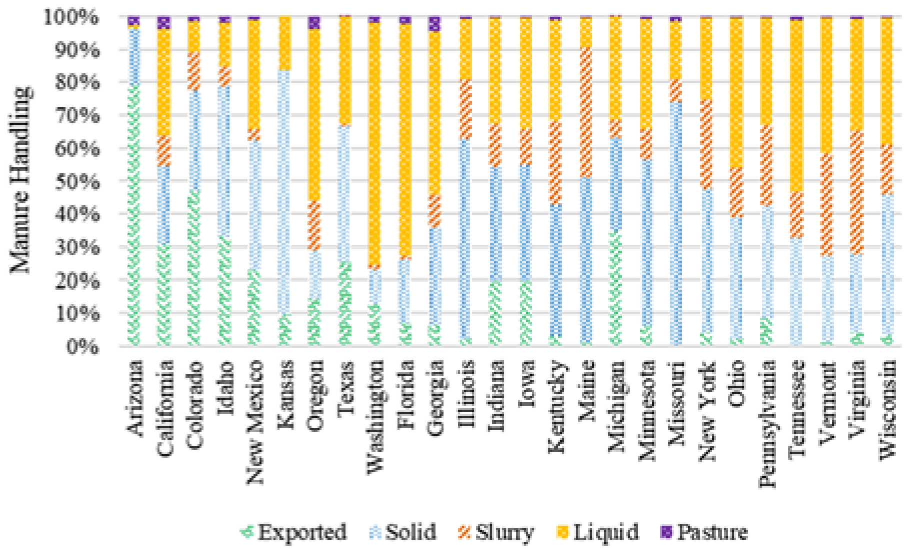
The nitrogen excretion values also look high. I will use Idaho as an example again, the value is 162 kg/animal/year. I calculate 138 kg/animal/year using some of the latest equations and assuming that cows are lactating for 305 days and dry for 60 with a birth weight of 680 (136 kg/animal/year for a birth weight of 600 which I think is closer to reality). Also, I calculate 50 kg/animal/d for heifers while a value of 69 is in the table. Below are the equations and references that I used.

Nitrogen excretion by lactating cattle										
NE = 20.3 + 0.654*NI			Reed et al., 2015							
NE = 7 + 0.710*NI			Yan et al., 2006							
NE = 30 + 0.67*NI			Kebreab 2010							
NE = (DMI *CP *84.1) + (BW x 0.196)				Nennich et al. 2005						
Lactating data averages										
DMI (kg)	CP (%)	NI (g/d)	BW (kg)		N excretion g/d/cow		N excretion kg/d/1000kg			ref
21.785	16.6	578.6096	600		398.7107		0.664518			Reed et al., 2015
21.785	16.6	578.6096	600		417.8128		0.696355			Yan et al., 2006
21.785	16.6	578.6096	600		417.6684		0.696114			Kebreab 2010
21.785	16.6	578.6096	600		421.7317		0.702886			Nennich et al. 2005
					413.9809		**0.689968**	average		
Nitrogen Excretion by Dry cows										
NE = 15.1 + 0.828*NI			Reed et al., 2015							
Dry Cow data averages										
DMI (kg)	CP (%)	NI (g/d)	BW (kg)		N excretion g/d/cow		N excretion kg/d/1000kg			
8.205	15.45	195	690		**176.56**		**0.255884**			Reed et al., 2015
Nitrogen Excretion by heifers										
NE = 15.1 + 0.828*NI			Reed et al., 2015							
NE = (DMI * CP * 78.39) + 51.4			Nennich et al. 2005							
Heifer data averages										
DMI (kg)	CP (%)	NI (g/d)	BW (kg)		N excretion g/d/cow		N excretion kg/d/1000kg			
7.175	14.4	159	531		146.752		0.276369			Reed et al., 2015
7.175	14.4	159	531		132.3925		0.249327			Nennich et al. 2005
					139.5723		**0.262848**	average		

Response: See response to Comment 30.

Comment 27: 2018 manure distribution among waste management systems by operation

I am concerned about the accuracy of the values in Table A-188 on page A-41. The figure below was generated by a post-doc working in the ARS lab in Pennsylvania, based on the ARMS data. It is total mass of manure on dairies in different storage. To me, this distribution looks a lot more realistic for Idaho at least if I assume 100% of the manure exported was a solid. When I did my own "survey" I came up with about 76% of total manure stored as a solid. Discrepancies for other major dairy states are also present compared to this.



There also seems to be other manure data in ARMS so I am a bit perplexed by it. This would obviously have a very large impact on the values calculated and I think more work in this area could be done.

Response: See response to Comment 30.

Comment 28: Methane conversion factors for dry systems
Below are the most recent values in the new IPCC refinement that differ from Table A-191 on page A-45.

Waste Management System	Cool Climate MCF	Temperate Climate MCF	Warm Climate MCF
Cattle deep litter (<1month)	2.75	6.5	18
Cattle deep litter (>1month)	21-26	37-41	73-76
Composting static pile	1	2	2.5
Composting Extensive/passive	1	2	2.5
Dry Lot			2

They also had a new value for pasture of 0.45 but that was assuming you used a B_0 of 19.

Response: See response to Comment 30.

Comment 29: Direct N_2O emission factors
Below are the most recent values in the new IPCC refinement that differ from Table A-193 on page A-47.

Waste management system	Direct N_2O EF

Anaerobic Digester	0.0006
Composting intensive	0.005
Composting Passive	0.005
Composting Static (force aeration)	0.10
Liquid/slurry	0.005 w/ cover 0/without
Solid Storage	0.010

Response: See response to Comment 30.

Comment 30: Indirect N_2O loss factors
One basic question here, % of what lost? Total N from the storage? N fed? Below are the most recent values in the new IPCC refinement that differ from what you have in the current table.

Do you account for additives such as Alum that will greatly reduce NH_3 emissions?

Animal Type	Waste Management System	Volatilization Nitrogen Loss
Beef Cattle	Dry Lot	30*
Beef Cattle	Liquid/Slurry	15
Beef Cattle	Pasture	7
Dairy Cattle	Anaerobic Lagoon	35**
Dairy Cattle	Daily Spread	7
Dairy Cattle	Deep Pit	25
Dairy Cattle	Dry Lot	45
Dairy Cattle	Liquid/slurry	48
Dairy Cattle	Solid Storage	30
Poultry	Anaerobic Lagoon	40
Poultry	Liquid/slurry	40
Poultry	Manure with bedding	40#
Poultry	Manure without bedding	48
Poultry	Solid Storage	40
Swine	Anaerobic Lagoon	40
Swine	Deep Pit	25
Swine	Liquid/Slurry	48

*Research shows that ~50% of N fed is lost as NH_3 from feedlots.
**Our on-farm research has shown that 65 percent of total N was lost from lagoon storage over the year (Leytem et al., 2018).

<u>References</u>

Arndt, C., A. B. Leytem, A. N. Hristov, D. Zavala-Araiza, J. P. Cativiela, S. Conley, C. Daube, I. Faloona, and S. C. Herndon. 2018. Short-term methane emissions from 2 dairy farms in California estimated by different measurement techniques and US Environmental Protection Agency inventory methodology: A case study. J. Dairy Sci. 101:11461–11479, https://doi.org/10.3168/jds.2017-13881

Balde H., VanderZaag A.C., Burtt S., Evans L., Wagner-Riddle C., Desjardins R.L., MacDonald J.D. (2016) Measured versus modeled methane emissions from separated liquid dairy manure show large model underestimates. Agriculture Ecosystems & Environment 230: 261-270. doi: 10.1016/j.agee.2016.06.016.

J. Habtewold, R. J. Gordon, J. D. Wood, C. Wagner-Riddle, A. C. VanderZaag, and K. E. Dunfield. 2017. Dairy Manure Total Solid Levels Impact CH4 Flux and Abundance of Methanogenic Archaeal Communities. J. Environ. Qual. 46:232–236 doi:10.2134/jeq2016.11.0451

E. Kebreab, A.B. Strathe, J. Dijkstra, J.A.N. Mills, C.K. Reynolds, L.A. Crompton, T. Yan, and J. France.

2010. Energy and protein interactions and their effect on nitrogen excretion in dairy cows

Leytem A.B., Bjorneberg D.L., Koehn A.C., Moraes L.E., Kebreab E., Dungan R.S. (2017) Methane emissions from dairy lagoons in the western United States. Journal of Dairy Science.

Lory, John A., R. E. Massey, and J. M. Zulovich. 2010. An Evaluation of the USEPA Calculations of Greenhouse Gas Emissions from Anaerobic Lagoons. J. Environ. Qual. 39:776–783 doi:10.2134/jeq2009.0319

Leytem, A. B., D. L. Bjorneberg, C. A. Rotz, L. E. Moraes, E. Kebreab, R. S. Dungan. 2018. AMMONIA EMISSIONS FROM DAIRY LAGOONS IN THE WESTERN U.S. Transactions of the ASABE Vol. 61(3): 1001-1015

Miranda, Nicole D., Ramón Granell, Hanna L.Tuomisto, Malcolm D.McCulloch. 2016. Meta-analysis of methane yields from anaerobic digestion of dairy cattle manure. Biomass and Bioenergy Volume 86, March 2016, Pages 65-75. https://doi.org/10.1016/j.biombioe.2016.01.012

Nennich, T. D., J. H. Harrison, L. M. VanWieringen, D. Meyer, A. J. Heinrichs, W. P. Weiss, N. R. St-Pierre, R. L. Kincaid, D. L. Davidson, and E. Block. 2005. Prediction of Manure and Nutrient Excretion from Dairy Cattle. J. Dairy Sci. 88:3721–3733.

Reed, K. F., L. E. Moraes , D. P. Casper , and E. Kebreab. 2015. Predicting nitrogen excretion from cattle. J. Dairy Sci. 98 :3025–3035 http://dx.doi.org/ 10.3168/jds.2014-8397

Rico, Carlos, José Luis Rico, Hipólito García, Pedro Antonio García. 2012. Solid – Liquid separation of dairy manure: Distribution of components and methane production. Biomass and Bioenergy Volume 39, April 2012, Pages 370-377. https://doi.org/10.1016/j.biombioe.2012.01.031

Wolf, Julie, Ghassem R. Asrar and Tristram O. West. 2017. Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock Carbon Balance Manage (2017) 12:16, DOI 10.1186/s13021-017-0084-y

Response: EPA appreciates the commenter's suggestions to improve the accuracy and clarity of the chapter describing GHG emissions from manure management (Chapter 5.2) and recognizes the commenter's specific data recommendations to potentially improve emissions estimates. EPA is regularly reviewing literature and available data sources for updated activity data including methane producing potential, volatile solids and nitrogen excretion rates, waste management system usage data, methane conversion factors, and emission factors. Note that volatile solids and nitrogen excretion rates for cattle are reliant on underlying data provided in Chapter 5.1 (Enteric Fermentation), which EPA acknowledges is also an area for potential improvements. EPA appreciates the commenter for confirming known available data and applicable references; EPA will review these items as resources allow. EPA is aware of IPCC's 2019 Refinement to 2006 IPCC Guidelines for National Greenhouse Gas Inventories and plans to review updated methodologies and emission factors as resources allow, as noted in the Planned Improvements section of Chapter 5.2.

Chapter 6. LULUCF

No comments received.

Chapter 7. Waste

Landfill Specific

Comment 31: Pulp and paper industrial wastewater and landfill emissions

NCASI independently calculated pulp and paper industrial wastewater CH_4 emissions given in Table 7-11 on 7-23 of the draft report (the value reported is 0.6 MMT CO2eq.), and NCASI's result conforms to the pulp and paper result in Table 7-11. NCASI appreciates the high level of quality in the draft report regarding pulp and paper industry wastewater CH_4 emissions.

NCASI calculated CH_4 emissions of 4.5 MMT CO_2eq. from pulp and paper industrial landfills using 2018 EPA GHG reporting program (GHGRP) data. Within the draft report, NCASI could only locate CH_4 emissions from all industrial landfills (15.0 MMT CO_2eq. for 2018 found in Table 7-3 on 7-3). NCASI would appreciate confirmation that the 4.5 MMT CO_2eq. from pulp and paper industrial landfills that NCASI calculated from GHGRP data is the same number EPA is using for their calculations for CH_4 emissions from all industrial landfills.

Response: EPA appreciates the commenter's feedback regarding the accuracy of the pulp and paper industrial wastewater methane emissions estimates. With regard to the emissions estimates for pulp and paper industrial landfills, EPA added text to the section titled "Methodology Applied for Industrial Waste Landfills," within section 7.1 of the Inventory text, to clarify that EPA is currently unable to use the net emissions data directly reported to the GHGRP for industrial landfills because the waste disposal information does not correlate well for all industrial waste landfills accounted for in the Inventory estimates. Therefore, EPA is maintaining our current approach to estimating emissions from industrial waste landfills using production data from the pulp and paper and food and beverage sectors.

Comment 32: Datasets of quantities of industrial food processing waste disposed of in industrial waste landfills
EPA conducted an analyses of industrial food processing waste[1] in 2012. According to that report, although solid waste management data is not available, the primary method for managing solid waste from food processing sector is for utilization. These include animal feed, raw material for other products or direct utilization on agricultural land. Given the report's suggestion that very little food processing waste is landfilled, it would also be unlikely that food processors would spend the own or operate industrial landfills. The little food waste that is generated would more likely be redirected for composting or to a municipal solid waste landfill. This comports with industry experience.

The industry also evaluated the dataset for industrial waste landfills and found that very few of them represent food waste processing landfills. Those that do are primarily sugar facilities. In addition, for facilities that were unclear, we queried a few of the large generators that report under subchapter TT. Based on responses received, none of them are food waste facilities.
Response: EPA notes the information provided by the commenter on industrial food processing waste, including the EPA analyses from 2012. In the next Inventory cycle, EPA will further investigate the prevalence of food-related waste deposited in industrial waste landfills. EPA intends to record any findings from this exercise in a memorandum and if any changes to the methodology or assumptions for industrial waste landfills are warranted, EPA will implement the changes. Please see the "Planned Improvements" in Section 7.1.

Comment 33: Unpublished waste characterization studies from 1990
EREF has a assembled a comprehensive list of waste characterization studies including those evaluated by EPA. They plan on using reliable data from those studies to reevaluate the DOC values for the duration of the period from 1990 onward. This analysis will inform updates to the 2016 paper provided to EPA and reinforce industry's previous request to update the GHGRP as well as the US GHG Inventory specifically for years 2005-present. EREF expects to conclude its update to the White Paper by February 2020.

We understand that EPA is focused on the period from 1990-2004 because it falls outside the GHGRP timeframe. However, data from waste characterization studies indicate the MSW fraction in the waste stream has steadily declined since around 2000. As previously stated, EREF obtained additional information to further substantiate the steady decline in the MSW fraction of waste disposed of in MSW landfills necessitating updates to the DOC values for 2005 to the present to more accurately represent landfill emissions. Therefore, EPA should extend the time period from 2005 to current. We also request EPA to update the GHGRP with revised DOC values for calculating MSW Landfill emissions.

Response: EPA notes the commenter's feedback on the decline in the MSW fraction of waste disposed in MSW landfills. EPA looks forward to reviewing the work by EREF to update their 2016 paper. As stated in the Planned

Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA is developing a multivariate analysis using publicly available data directly reported to the GHGRP solving for optimized DOC and k-values across the more than 1,100 landfills that reporting to the program. The results of this analysis could help inform a future GHGRP rulemaking where changes could be made to the default DOC and k-values contained within Subpart HH of the GHGRP which could then be carried over to the Inventory emissions estimates for MSW landfills upon promulgation of any revisions to 40 CFR Part 98.

Comment 34: Decay rate values

The attached article provides information on additional first order decay models for landfill gas production. It describes two Dutch models; one from TNO (The Netherlands Organization of Applied Scientific Research) and another from Afvalzorg (Dutch waste company).

Response: EPA appreciates the articles provided by the commenter and will review them in the context of Planned Improvements to the Inventory estimates.

Comment 35: Scale-up factor methodology for landfills

We find the explanation of the methodology EPA employed to arrive at the scale-up factor to be clear. However, based on reasonable expectations that landfills that do not report under the GHGRP are likely to be smaller, closed sites with declining GHG emissions and that reporting landfills will continue to represent a larger proportion of WIP, we recommend that EPA routinely evaluate and revise the scale-up factor. For example, since starting in 2010, every year fewer landfills report more than the 25,000 MT CO_2eq. Yet, every year, more landfills are included in the GHGRP. This means that more of the waste is covered by reporting facilities on an annual basis.

Year	# of landfills reporting	# of landfills >25k MT CO_2eq.	Total MT CO_2eq. reported
2010	1235	975	101,920,033
2011	1240	965	93,830,839
2012	1252	961	94,375,699
2013	1278	946	91,159,615
2014	1290	941	90,817,217
2015	1294	935	89,746,871
2016	1300	914	86,905,137
2017	1304	898	86,464,158
2018	1313	896	89,215,401

Again, most landfills that are exempt from the GHGRP requirements are old, small, closed landfills. The potential methane emissions from these sites decrease year over year by approximately 3 percent, on average. Therefore, the emissions contribution from these sites will continue to decrease compared to the sites that report via the GHGRP. The scaling factor must be adjusted to reflect the declining contribution of the exempt sites.

Response: EPA appreciates the commenter's feedback on the clarity of the methodology used to develop the scale-up factor to account for landfills that do not report to the GHGRP. EPA also agrees with the commenter's feedback that the scale-up factor should be evaluated on a routine basis. There is a large amount of uncertainty associated with the number of non-reporting landfills and their total waste-in-place and the scale-up factor is our best estimate given the available information. EPA plans to reexamine the scale-up factor for the 1990-2019 Inventory cycle to determine if there are additional landfills reporting to the GHGRP such that the waste-in-place amounts for those landfills can be removed from the scale-up factor assumptions. As the same time, EPA will also account for those landfills that have stopped reporting to the program because they were able to exercise the off-ramp. Any additional information from commenters on landfills that do not report to the GHGRP that could help refine the scale-up factor assumptions are always welcome and appreciated.

Comment 36: Methane oxidation factor
Our previous years' comments on methane oxidation factor used for the period 1990 – 2004 in the inventory time series remain unchanged and are repeated below. EPA calculates a national estimate of methane generation and emissions using a combination of secondary data sources that detail the annual quantity of waste landfilled and the annual quantity of methane recovered from facilities with landfill gas collection and control systems. EPA applies a 10% oxidation factor to all facilities for the years 1990 to 2004. This ten percent default factor contrasts significantly with the average methane oxidation factor of 19.5 percent applied through use of GHGRP data, to the later years of the time series (2005 to 2016). Importantly, the 19.5 percent average oxidation rate incorporated in the GHGRP, subpart HH emissions data is premised on a more detailed and up-to-date estimation approach than is the default value of 10 percent. It is also a conservative average value, as the GHGRP methodology restricted the maximum oxidation rate to 35 percent.

In its work to review and revise the method for calculating methane oxidation under subpart HH of the GHGRP, EPA acknowledged the need to update the default 10 percent oxidation value. The default value was based on only one field study, at a landfill without gas collection and control, and did not reflect the much higher oxidation values found in numerous subsequent, peer-reviewed field studies. Given the plethora of scientific studies showing methane oxidation to be several times higher than the EPA and IPCC default value, we strongly recommend EPA apply a revised value (perhaps the average oxidation value from the GHGRP) to the earlier years of the time series.

Response**: EPA appreciates the commenter's feedback on the oxidation factor as applied to estimating emissions from MSW landfills. EPA regularly reviews new literature related to landfill methane oxidation and investigated options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux) or the average oxidation factor across facilities reporting to the GHGRP (approximately 19.5 percent). At this time EPA has decided not to revise the methane oxidation factor for the 1990-2004 time series since such a change will likely result in a noticeable discontinuity in the emissions between 2004 and 2005-2010 (i.e., a jump in emissions between 2004 and 2005) that would need to be investigated and resolved to ensure methodological consistency over the time series and to accurately reflect trends. We continue to advance efforts to improve the methane generation calculations in the landfills section of the Waste Chapter by focusing on improvements to the DOC and k-value per responses to other comments submitted by this commenter, in order to make best use of the available resources across the Inventory compilation process.

Comment 37: Degradable organic carbon (DOC)
Chapter 7 of the draft inventory explains that EPA uses one DOC value of 0.20 to calculate emissions for the years 1990 through 2004, and uses emissions reported through the GHGRP for years 2005 through 2017. The GHGRP allows landfills to use 0.20 for bulk MSW or allows a landfill to further delineate waste streams by accounting for separate shipments of C&D waste, which uses a DOC of 0.08, and separate shipments of inert wastes, which may use a DOC of 0.0. If a landfill delineates in this way, it must use a DOC of 0.31 for its MSW waste volumes, which applies an artificially high DOC to MSW, and inappropriately overestimates emissions. The required DOC value of 0.31 fails to account for the significant volumes of C&D and inert wastes that are incorporated in MSW, and which cannot be separated from the MSW or accounted for distinctly, as can discrete shipments of inert wastes from industrial or C&D recycling facilities.

While we are pleased to learn that EPA plans to revisit the DOC value of 0.20, we question why the Agency is focusing first on the early years of the inventory rather than the later portion of the time series. We believe that the fundamental shifts in the characterization of waste disposed in landfills has occurred in the later portion of the time series and that the research conducted thus far by state agencies and the Environmental Research and Education Foundation (EREF) are illustrative of those changes. We strongly recommend that EPA instead first focus on the second half of the time series and reevaluate the DOC values incorporated in subpart HH of the GHGRP, which underpins the data used for those years of the inventory.

In 2016, the Environmental Research and Education Foundation (EREF) undertook a state-based study of DOC values for both landfills receiving only MSW (MSW Only Landfills) and for Non-MSW Material going to MSW Landfills. EREF updated the 2016 paper in January 2019 with additional information and is again in the process of making further revisions based on new waste characterization information. The DOC guideline recommended by EPA for MSW Only Landfills is 0.31 and the recommended guideline for bulk material (combined MSW, C&D and inert waste streams) going to MSW landfills is 0.20. EREF concluded both of these guidelines over-estimate the amount of organic waste deposited in landfills, which results in inaccurate estimates of landfill gas generation and methane emissions. Furthermore, neither of the EPA-recommended DOC values have been reviewed in many years. It is time EPA update the DOC values for MSW and Bulk waste and we believe that the most valuable focus would be to reassess the DOC values incorporated in the GHGRP used for inventory years 2005 forward.

EREF reviewed 17 recent waste composition studies for MSW Only Landfills conducted by 13 states and confirmed that waste composition has and continues to change over time, as fewer organic materials are sent to MSW landfills. Since EPA cites the EREF research as a rationale for reassessing DOC values for 1990-2004, the following quotes from EREF clearly suggest that the data strongly suggest reevaluating DOC values used in the GHGRP for years 2005 and later:

> All characterization studies had DOC_{MSW} values significantly less than the default value of 0.31, which suggests this value is not representative of real-world conditions for MSW (Table 3; Figure 4). Analysis of U.S. EPA data … also results in a significantly lower DOC_{MSW} value compared to the U.S. EPA guideline of 0.31, with DOC_{MSW} values ranging from 0.218 in 1994 to a minimum of 0.160 in 2015 (Figure 4; Appendix B). Both the state characterization studies and U.S. EPA Facts and Figures data independently suggest that a DOC guideline value of 0.31 for MSW is not representative of the landfilled MSW stream. …
>
> The use of a single DOC value as a guideline for all U.S. landfills makes the implicit assumption that waste composition does not change over time or due to location. The results presented here suggest these are not valid assumptions and that, collectively, the use of a static DOC value of 0.31 may lead to inaccurate estimates of landfill gas emissions for landfills that only accept MSW. Because this specific analysis is focused only on MSW materials, one would expect the inclusion of non-MSW materials going to a landfill to impact DOC estimates even more.[2]

With respect to Non-MSW going to MSW Landfills, EREF finds "a common assumption is that all waste materials entering MSW landfills consist only of MSW materials. As noted previously, MSW Landfills rarely accept MSW exclusively. Rather, most MSW Landfills (landfills in 45 states) are authorized to accept other Subtitle D wastes in addition to MSW."[3] In addition, EREF notes:

> Given that a third of incoming waste to MSW Landfills consists of non-MSW materials, there is significant potential for non-MSW materials to impact the relative fraction of organics and degradable organic carbon (DOC) of the MSW Landfill waste stream.[4]
>
> The amount and types of non-MSW Subtitle D organic wastes impact the DOC value for the landfilled waste since it consists of both MSW and non-MSW streams. This combined DOC value (DOC_{SubD}) incorporates degradable organic carbon from all Subtitle D wastes accepted at MSW Landfills (both MSW and non-MSW). … State waste characterization studies were used to estimate the relative fraction of each organic constituent for C&D and industrial waste … and DOC for each waste type was calculated using Equation 1b. Based on this analysis the DOC_{SubD} value of landfilled waste is 0.167 (Table 7)."[5]

EREF also highlights that the DOC_{SubD} value:

> … is lower than the guideline value of 0.20 for bulk waste. It is also lower than the average DOC_{MSW} value of 0.191 computed in the prior section, indicating the inclusion of non-MSW decreases overall DOC. Using the

> same approach as for the DOC_{MSW} analysis, state-specific organics content and DOC_{SubD} values for all fourteen states with sufficient data were determined and presented in Table 8, below. … The results, all for 2013, highlight differences in DOC_{SubD} based on locale and suggest the use of a static 0.20 guideline for bulk waste may lead to inaccurate estimates of methane generation and emissions, especially in some areas.[6]

Thus, EREF concludes as follows:

> The average computed DOC value for MSW using state data was 0.191, or roughly three-fifths of the MSW guideline value. The average computed DOC value for bulk waste using state data was 0.167, or roughly four-fifths of the bulk waste guideline. This analysis suggests that the U.S. EPA's guideline DOC values of 0.31 for MSW-only landfills and 0.20 for facilities accepting non-MSW Subtitle D wastes overestimate DOC at these landfills and may result in inaccurate estimates of landfill gas generation and methane emissions.[7]

Based on this review of the DOC values for MSW landfills, the waste sector concludes that the long-standing DOC values developed in the past over-estimate both landfill gas generation and methane emissions. The data provided by EREF confirms that two trends are driving the changes in waste composition at MSW Landfills. First, many MSW Landfills are handling less organic matter now, and we anticipate this trend will continue due to state and local organics diversion goals. Second, the increase of Subtitle D non-MSW waste disposed has altered the DOC for all waste deposited in MSW Landfills. EPA validates these trends in the Inventory's Chapter 6 discussion of carbon sequestration of harvested wood products, yard waste and food waste, which shows a significant reduction in sequestered carbon since 1990 due to reduced volumes of organic wastes disposed in landfills.

Based on EREF's research, we urge EPA to update the DOC values to reflect significant changes in the amounts and types of organic materials being landfilled over the past 20 years. The values now in use are inaccurate and should not be used going forward. We recommend that EPA review and update the DOC values for the entire time series for the 2019 version of the GHG Inventory, and prioritize updates of the DOC values used in calculating GHG emissions under Subpart HH of the GHGRP.

Further, as EPA clearly recognizes that the composition of the waste at MSW Landfills has changed and continues to change, we suggest the Agency add an additional factor, "(5) the composition of the waste" to the sentence on line 42, page 7-2 of the waste chapter that begins: "Methane generation and emissions from landfills are a function of several factors."

[2] The Environmental Research & Education Foundation (2019). Analysis of Waste Streams Entering MSW Landfills: Estimating DOE Values and the Impact of Non-MSW Materials. Retrieved from www.erefdn.org. pp. 8 - 9.
[3] Ibid., p. 10.
[4] Ibid., p. 11.
[5] Ibid., p. 13.
[6] Ibid., p. 14.
[7] Ibid., p. 15.

Response: As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA is developing a multivariate analysis solving for optimized DOC and k- across the more than 1,100 landfills that report under subpart HH of the GHGRP. This analysis uses publicly available data directly reported to the GHGRP. The results of this analysis could inform updates to the default DOC and k-values used by landfills subject to reporting under subpart HH of the GHGRP in calculating their facility level emissions. For updates to the DOC to be reflected in the Inventory, the updates also need to be incorporated in Subpart HH of the GHGRP given its direct use in estimating national-level emissions from MSW landfills.

With regard to the suggested text edit, EPA has already reflected the importance of waste composition with the sentence that begins "Methane generation and emissions from landfills are a function of several factors, including (1) the total amount <u>and composition</u> of waste-in-place…."

Comment 38: The k factor (Methane generation rate constant)
Our previous years' comments on k factors remain unchanged and are repeated below. The waste sector strongly supports EPA's plans to review these k values against new data and other landfill gas models, as well as assess the uncertainty factor applied to these k values in the Waste Model. We have been concerned that these k-values are outdated and rife with uncertainty, as confirmed by the *Draft AP 42.2.4 Municipal Solid Waste Landfills*, which states:

> There is a significant level of uncertainty in Equation 2 and its recommended default values for k and L_o. The recommended defaults k and L_o for conventional landfills, based upon the best fit to 40 different landfills, yielded predicted CH_4 emissions that ranged from ~30 to 400% of measured values and had a relative standard deviation of 0.73 (Table 2-2). The default values for wet landfills were based on a more limited set of data and are expected to contain even greater uncertainty.[8]

The waste sector has previously highlighted the significant issues with the k values used in the Draft AP-42 Section 2.4: Municipal Solid Waste Landfills. In fact, EPA has never finalized AP-42 for MSW landfills, despite the k-value issues identified *<u>by EPA</u>* in both AP-42 and the Background Information Document. With uncertainties in CH_4 emissions ranging from -30% to 400% under EPA's assessment of the LandGEM model, it is difficult to rely on these data. For this reason, we support EPA's plan to review and resolve the significant problems in the k value data set. However, we also suggest review L_0 value. Although an independent variable, L_0 should be considered in conjunction with k value modifications because it is related to fitting the curve, where the results will be dependent on the assumptions used for the L_0/DOC.

[8] U.S. EPA, *Draft AP 42.2.4: Municipal Solid Waste Landfills*, October 2008, p. 2.4-6.

Response: As stated in the Planned Improvements section of Section 7.1 of the U.S. Greenhouse Gas Inventory of Emissions and Sinks, EPA is developing a multivariate analysis solving for optimized DOC and k-values across the more than 1,100 landfills that report under subpart HH of the GHGRP. This analysis uses publicly available data directly reported to the GHGRP. The results of this analysis could inform updates to the default DOC and k-values used by landfills subject to reporting under Subpart HH of the GHGRP in calculating their facility level emissions. As the commenter already acknowledged for updating DOC, for updates to the k-value to be reflected in the Inventory, the updates also need to be incorporated in Subpart HH of the GHGRP given its direct use in estimating national-level emissions from MSW landfills.

Composting Specific

Comment 39: Datasets on industrial composting facilities

The waste sector does not have datasets on industrial composting facilities located in U.S. territories.

Response: EPA appreciates the commenter's feedback on the current lack of datasets on composting facilities in U.S. territories.

Comment 40: Compost emission factor
Our previous years' comments on compost emission factor remain unchanged and are repeated below. In ideal conditions, the composting process occurs at a moisture content of between 50 and 60%, but the moisture content of feedstocks received at composting sites varies and can range from 20% to 80%. It is common for moisture to be added to dry feedstocks prior to the start of composting to optimize the biological process. In the calculation of emissions from composting in the draft chapter, it appears that all incoming wastes were assumed to have a moisture content of

60%. If 60% is not reflective of the actual weighted average of all feedstocks, this will introduce errors in the inventory calculation that could be significant.

We recommend that the calculations be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents, or ask that further information be provided on the rationale for assuming 60% as the average moisture content of all inbound materials.

Response: EPA notes the commenter's feedback on the moisture content levels used in the calculation of emissions from composting. The calculations for composting are based on IPCC Tier 1 methodology defaults. Under this methodology, the emission factors for CH_4 and N_2O assume a moisture content of 60% in the wet waste. (IPCC 2006) EPA has included this detail to the Methodology section of Section 7.3 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018, as was done in the previous year's inventory report, so that the source of the moisture content is more transparent. In addition, EPA continues to include in the Planned Improvements section of Section 7.3 that EPA is looking into the possibility of incorporating more specific waste subcategories and category-specific moisture contents into the emissions estimates for composting in the United Stated to improve accuracy. However, to date the EPA has not been able to locate substantial information on the composition of waste at U.S. composting facilities to do so. As additional data becomes available on the composition of waste at these facilities, EPA will consider using this information to create a more detailed calculation of U.S. composting emissions.

Appendix A: List of Reviewers and Commenters

EPA distributed the expert review chapters of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* to a list of ~220 expert reviewers across all sectors of the Inventory. The list below includes names of those expert reviewers who submitted comments as part of the Expert Review Period.

- April Leytem - United States Department of Agriculture (USDA)
- Anne Germain - Waste Management, Republic Services, National Waste & Recycling Association, Solid Waste Association of North America, SCS Engineers, and Weaver Consulting Group
- Barry Malmberg - National Council for Air and Stream Improvement (NCASI), Inc.
- David Lax- American Petroleum Institute (API)
- Jesse Maxwell - Waste Management, Republic Services, National Waste & Recycling Association Solid Waste Association of North America, SCS Engineers, and Weaver Consulting Group
- Jeremy Martin – Union of Concerned Scientists (UCS)
- John Davies – United States Department of Transportation (USDOT)
- Stephen Jasinski – National Minerals Information Center United States Geological Survey (USGS)

Note: Names of commenters are listed in no particular order.

Appendix B: Dates of review

- Energy: October 17 - November 15, 2019
- Industrial Processes and Product Use (IPPU): October 17-November 15, 2019
- Waste: October 17 - November 15, 2019
- Agriculture: October 28 – November 25, 2019
- Land Use, Land Use Change and Forestry (LULUCF): November 13 – December 13, 2019

Appendix C: EPA Charge Questions to Expert Reviewers

To facilitate expert review and indicate where input would be helpful, the EPA included charge questions for the Expert Review Period of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* report. EPA also noted to expert reviewers that while these charge questions were designed to assist in conducting a more targeted expert review, comments outside of the charge questions were also welcome. Included below is a list of the charge questions by Inventory chapter.

Energy

Requests for Expert Feedback for the 1990-2018 Energy Chapter

General Questions:

1. Please provide your overall impressions of the clarity and transparency of the Energy chapter.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Energy chapter.

Source-Specific Questions:

Fossil Fuel Combustion: CO2 from Fossil Fuel Combustion

1. Please provide your overall impressions of the clarity of the discussion of trends in CO2 emissions from fossil fuel combustion. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity.
2. Data for energy use in U.S. Territories comes from the International Energy Statistics provided by EIA. This source has data only through 2014; the years 2015 through 2018 are proxies. Are there other sources of U.S. Territory energy use that could be used?
3. Facility-level combustion emissions data from EPA's GHGRP are currently used to help describe the changes in the industrial sector. Are there other ways in which the GHGRP data could be used to help better characterize the industrial sector's energy use? Are there ways the industrial sector's emissions could be better classified by industrial economic activity type?

Fossil Fuel Combustion: CH4 and N2O from Stationary Combustion

1. The CH4 and N2O emission factors for the electric power sector are based on a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. For all other stationary sectors, the emission factors used in Tier 1 methods are primarily taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Are there other more U.S.-specific CH4 and N2O emission factor data sources that could be utilized, especially for natural gas combustion sources?

Carbon Emitted from Non-Energy Uses of Fossil Fuels

1. Please provide your overall impressions of the clarity of the discussion of Carbon Emitted from Non-Energy Uses of Fossil Fuels. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity, especially in relation to linkages with the estimates in the IPPU chapter.

Gasoline Carbon Factor

Gasoline Component Composition:

1. Is the EPA Trends data a good data source for determining gasoline composition? Are there other sources available, including for the full time series 1990-2018 and going forward?
2. Is it reasonable to apply the EPA Trends data across all fuel types (i.e., California fuels not included)?
3. Should the EPA Trends data be used for the full time series or just for years where the NIPER data is not available?
4. If using across the time series, is it reasonable to apply the 1997 results to 1990-1996 and the 2016 results to 2017-2018?

Component Speciation:

1. Is it reasonable to use the API data to speciate gasoline components?
2. Is the approach outlined in Annex 2 of this memo to develop the gasoline speciated components reasonable (see p. 15)?
3. Is the API data representative of different gasoline types? If not, is there a better approach to use?
4. Is the API data representative over time? If not is there a better approach?
5. Are there other gasoline speciation data available?
6. Would it be better to use a representative molecule to represent carbon content of different gasoline components?

Carbon Factor:

1. The carbon factor of each gasoline component is based on a percent by mass and are distributed across the full fuel based on the density of the entire gallon. Should individual densities be used instead? If so is there a good source of data for these densities?
2. The carbon factors are lower than what was found previously; do the updated values seem reasonable?

Heating Value:

1. Is the approach for developing heating values reasonable?
2. Are there other data sources available on heating content?
3. The factor is slightly higher than current factors used; do the update seem reasonable?

See also attached at the end of Appendix C two additional technical memo outlining proposed improvements to emission factors for On-Highway CH_4 and N_2O and Emission Factors Gasoline CO_2 Emission Factors.

Industrial Processes and Product Use (IPPU)

Requests for Expert Feedback for the 1990-2018 IPPU Chapter

General Questions:

1. Please provide your overall impressions of the transparency of the IPPU chapter.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the IPPU chapter.
3. For the source categories included in the expert review draft, is the state of the industry current and accurately described? Are there technologies, practices, or trends that EPA should consider?

Source-Specific Questions:

Minerals

1. **Other process uses of carbonates -** Please provide information on:
   - Data on carbonate use in non-metallurgical magnesium production.
   - Data on carbonate use in the production of ceramics.

Chemicals

2. **Caprolactam, Glyoxal and Glyoxylic Acid Production** - With the inclusion of this new IPPU source category as of the last Inventory, EPA requests feedback on the overall chapter text, assumptions and information on the state of the industry.
3. **Calcium Carbide Production** - Please provide input on data sources and industry information on production to estimate emissions using IPCC methods.
4. **Phosphoric Acid Production**: Please provide input on data sources and assumptions regarding phosphate rock including:
    - Regional production data and the assumption that 2018 regional production was estimated based on regional production data from 2005 to 2011.
    - The carbonate composition of phosphate rock and how it varies depending upon where the material is mined and over time.
    - The disposition of the organic carbon content of the phosphate rock and the assumption that it remains in the phosphoric acid product and is not released as CO_2. This includes feedback on the assumption that all domestically produced phosphate rock is used in phosphoric acid production and it is used without first being calcined.

Metal Production

5. **Zinc Production**: The EPA seeks comments on assumptions applied to determine the split between primary and secondary zinc production based on U.S. Geological Survey national totals. Are other options/data sources available to distinguish between process production totals?
6. **Iron and Steel Production**: The EPA seeks data on carbonaceous material (other than coking coal) consumption and coke oven gas production from merchant coke plants.

Other IPPU Categories

7. **ODS Substitutes -** The EPA seeks comments on possible sources of hydrofluorocarbon (HFC) use that are not reflected, or whose use is modeled lower than actual, as evident from a comparison of the underlying model with data reported under EPA's Greenhouse Gas Reporting Program (GHGRP).

Agriculture

Request for Expert Feedback for the 1990-2018 Agriculture Chapter

General Questions:

1. Provide your overall impressions of the clarity and transparency of the Agriculture chapter.
2. Provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Agriculture chapter.
3. Provide feedback on the methodologies, assumptions and activity data used to estimate emissions for categories within the Agriculture chapter.

Source-Specific Questions:

4. For the Manure Management source category, is the state of the industry current accurately described? Are there other technologies, practices, trends that we should consider?
5. Are the parameters and discussion of uncertainty within the Manure Management source category estimates adequately reflecting all uncertainties from this industry and the data EPA is currently using?

6. The Manure Management source category relies on national/regional livestock production and management data for calculating emissions estimates from USDA APHIS and NASS. Are there other/newer data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    a. Waste management system data, particularly seasonal changes in emissions from different WMS;
    b. Maximum methane producing capacity;
    c. Volatile solids and nitrogen excretion rates;
    d. Measured emission estimates (by waste management system) to help refine estimates of methane conversion factors.
7. For the Enteric Fermentation source category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider?
8. The Enteric Fermentation source category relies on national/regional livestock production, diet and management data for calculating emissions estimates. Are there other/newer data sources or methods that EPA should be aware of and consider in the calculating these emissions? Especially for:
    a. Dry matter/gross energy intake;
    b. Annual data for the DE, Y_m, and crude protein values of specific diet and feed components for foraging and feedlot animals;
    c. Monthly beef births and beef cow lactation rates;
    d. Weights and weight gains for beef and dairy cattle.
9. For the Enteric Fermentation source category and the Cattle Enteric Fermentation Model (CEFM), are the various regional designations of U.S. states (as presented in Annex 3.10) used for characterizing the diets of foraging cattle appropriate? The CEFM is used to estimate cattle CH_4 emissions from enteric fermentation, and incorporates information on livestock population, feeding practices, and production characteristics.

Land Use, Land-Use Change, and Forestry (LULUCF)

Request for Expert Feedback for the 1990-2018 LULUCF Chapter

General Questions:

1. Provide your overall impressions of the clarity and transparency of the categories provided in the attached draft LULUCF chapter.
2. Provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the attached draft LULUCF chapter.
3. Provide feedback on the methodologies and activity data used to estimate emissions for categories within the attached draft LULUCF chapter.

Category-Specific Questions

4. For the Yard Trimmings and Food Scraps category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider?
5. For the Yard Trimmings and Food Scraps category, are there other data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    - C storage, decay rates, etc. for yard trimmings and food scraps
    - Decay rates of food scraps, leaves, grass, and branches
    - National yard waste compositions
    - Precipitation range percentages for populations for the decay rate sensitivity analysis

Waste

Request for Expert Feedback for the 1990-2018 Waste Chapter

General Questions:

1. Please provide your overall impressions of the clarity and transparency of the Waste chapter.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Waste chapter.

Wastewater Specific Questions:

1. The wastewater source category relies on national production data from a variety of sources for calculating emissions estimates. Are there other data sources that EPA should be aware of and consider in the emissions calculations of this source?

2. Please provide input on any additional sources of wastewater outflow or BOD production that we may consider in our industrial methane emissions calculations. Do our estimates of the type of wastewater treatment systems in use seem reasonable?

3. For domestic wastewater emissions, please provide input on:
    a. Any additional sources for the N content of sludge, amount of sludge produced, and sludge disposal practices,
    b. National level data on the type of wastewater treatment systems in operation,
    c. National level data on the biogas generation and recovery operations,
    d. The estimates of the percent of BOD removed by aerobic, anaerobic, and other treatment systems for our methane estimates,
    e. The protein estimates and overall calculations for nitrous oxide. For example, do you have suggestions for developing a country-specific factor, rather than the IPCC default factor, to estimate the amount of nitrogen from industrial and commercial sources co-treated with domestic wastewater? and
    f. Sources of data for development of a country-specific methodology for N_2O emissions associated with on-site industrial wastewater treatment operations, including the appropriateness of using IPCC's default factor for domestic wastewater (0.005 kg N_2O-N/kg N).

4. Are there additional industries that are sources of methane or nitrous oxide emissions that should be included in the wastewater inventory? Are there available sources of national-level data for these industries?

5. Do you have suggestions for improving the discussion of our methodology? Is there any additional information that should be included to provide additional transparency?

6. Is the state of domestic and industrial wastewater treatment current and accurately described?

7. As stated in our Planned Improvements, EPA will be incorporating refinements to next year's Inventory based on IPCC's *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for -national-greenhouse-gas-inventories/)*. Are there any considerations you would like to bring to our attention, or other refinements that should be included?

Landfill-Specific Questions

1. Please comment on datasets that detail the quantities of industrial food processing waste that is disposed of in industrial waste landfills. The GHGRP dataset for industrial waste landfills includes a snapshot of select food

processing facilities, but vastly underestimates the entire food processing sector. The Inventory methodology applies a disposal factor to the annual amount of foods processed. Currently, we do not have a representative data set for this sector with which to improve the methodology.

2. A comprehensive Internet search by state was conducted to identify waste characterization studies published as of July 2018. We plan to conduct analyses to generate DOC values specific to the time frame of 1990 to 2004. This time frame is specified because the Inventory uses directly reported GHGRP net emissions, which incorporate the DOC values allowed under the rule, in years beyond 2004. Please comment and provide information on any additional studies that have not been published on the Internet from 1990 to date that may further these efforts.

3. An analysis is being conducted on decay rate values reported by select UNFCCC Annex 1 countries (e.g. Australia, Czech Republic, France, Germany, Italy, Norway, Spain, Sweden, Switzerland, Ukraine, and the United Kingdom) in their annual National Inventory Reports (NIR), as well as decay rate values used as defaults in first order decay models not used for NIR estimation, as compared to the U.S. Greenhouse Gas Inventory defaults used in the U.S. Waste model. This analysis is specific to the 1990 to 2004 time frame, because the Inventory uses directly reported GHGRP net emissions, which incorporate the decay rate values allowed under the rule, for years beyond 2004. Please comment and provide information on any additional studies and models, other than the ones listed below, that have not been published on the Internet from 1990 to date if any stakeholders have this information available to share.
    - LandGEM: (EPA 2005) Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide. EPA-600/R-05/047.
    - MSW DST: (NCSU and RTI 2000) Default Data and Data Input Requirements for the Municipal Solid Waste Management Decision Support Tool.
    - WARM: (EPA) Waste Reduction Model (WARM) Tool User's Guide. Version 14 (March 2016).
    - E-PRTR: (ADEME 2003) Outil de calcul des emissions dans l'air de CH4, CO2, SOx, NOx issues des centres de stockage de dechets menagers et assimiles Available at: https://www.declarationpollution.ecologie.gouv.fr/gerep/download/Annexe_2_Outil_de_calcul_ADEME_des_emissions_dans_lair_CH4_CO2_NOX_SO.pdf
    - MELMod: (Gregory et al. 2004) Review of Landfill Methane Emissions Modelling (MELMod). Submitted to the Department of the Environment, Food, and Rural Affairs.
    - GasSim: (GasSim 2.5 User Manual. 2018)

4. Additional information regarding the scale-up factor methodology used within the latter portion of the Landfills sector time series has been added to the Inventory Annex specific to landfill sin response to comments submitted by the UNFCCC. Please comment on the clarity of the more detailed scale-up factor methodology and its explanation and provide information on any portion of the approach that is unclear.

Composting-Specific Questions

Please comments on datasets available on industrial composting facilities located in the U.S. territories of Puerto Rico, Guam, U.S. Virgin Islands, Northern Mariana Islands, and American Samoa. We are aware of composting facilities in Puerto Rico. In order to accurately estimate GHG emissions from these facilities data is needed on the first year of operation, approximate annual quantities processed or number of households serviced, and whether the amount of waste composted is consistent from year to year.

Appendix D: Supplemental Technical Memos to Expert Reviewers for Energy Sector

1) On-Highway CH_4 and N_2O Emission Factors Update Memo
2) Gasoline C Factor Update Memo

Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Updated On-Highway CH_4 and N_2O Emission Factors

This memo provides research and analyses to support improvements to the transportation and mobile source component of the Inventory of U.S. Greenhouse Gas Emissions and Sinks. Improved on-highway gasoline and diesel vehicle methane (CH_4) and nitrous oxide (N_2O) emissions factors are estimated.

Summary

This memo details proposed updates to the on-highway CH_4 and N_2O emission factors used in the mobile source component of the U.S. Greenhouse Gas Inventory.

- **Current Method –** N_2O emission factors for gasoline and diesel Tier 2, Tier 3, LEV II and LEV III light-duty vehicles (LDV), light-duty trucks (LDT) and heavy-duty vehicles (HDV) are derived from a regression analysis done by EPA. CH_4 emission factors are calculated based on the ratio of NMOG emission standards.

- **Proposed Method –** Updated CH_4 and N_2O emission factors are derived from annual certification data for vehicles[1], to demonstrate compliance with federal vehicle emissions regulations.

Background

On-highway CH_4 and N_2O emission factors were last revised in 2017, based upon a regression analysis done by EPA for N_2O and the ratio of NMOG emission standards for CH_4.[2] Emission factors were developed for gasoline LDVs, LDTs and HDVs for Federal emission standard Tier 2, California emission standards LEV and, LEV II, and combined emission factors for the new Federal (Tier 3) and California (LEV III) emission standards. Federal and California emission standards are shown in Appendix A. Since that time, data from manufacturer testing of vehicles to meet certification standards have been published by EPA, providing sufficient data to update the emission factors for both gasoline and diesel on-highway vehicles.[3] Development of emission factors using these data will help improve the accuracy of the GHG inventory.

Assumptions

Tier 2, Tier 3, LEV II and LEV III emission standards (see Appendix A) include several emission bins to which manufacturers can certify vehicles, to meet a corporate average emission level which decreases over time. The proposed CH_4 and N_2O emission factors do not currently distinguish between emission bins but provide overall emission factors for each emission standard set. Data are not available to determine CH_4 and N_2O emission factors by emission bin.

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[1] https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment

[2] ICF, *Updated On-Highway CH_4 and N_2O Emission Factors for GHG Inventory,* Prepared for U.S. Environmental Protection Agency, October 2017.

[3] EPA, Certification and fuel economy data for passenger cars and trucks, available at https://www.epa.gov/sites/production/files/2019-02/light-duty-vehicle-test-results-report-2014-present.xlsx and https://www.epa.gov/sites/production/files/2019-02/heavy-duty-gas-and-diesel-engines-2015-present.xlsx

Calculations

Vehicle class is first determined from the Vehicle Class Description field in the compliance data. Average emission factors by vehicle class for gasoline vehicles are pulled directly from the compliance data. Table 1 compares the updated (new) emission factors against the emission factors currently used in the Inventory.

Table 1. Current and Proposed (New) CH_4 and N_2O Emission Factors for Onroad Gasoline Vehicles (g/mi)

Class	Standard	CH_4		N_2O	
		Current	New	Current	New
LDGV	Tier 2	0.008	0.007	0.008	0.005
	Tier 3	0.002	0.006	0.007	0.001
	LEV II	0.006	0.007	0.008	0.004
	LEV III	0.002	0.005	0.007	0.001
LDGT	Tier 2	0.008	0.010	0.008	0.003
	Tier 3	0.002	0.009	0.007	0.001
	LEV II	0.006	0.008	0.008	0.006
	LEV III	0.002	0.007	0.007	0.001
HDGV	Tier 2	0.008	0.030	0.017	0.002
	Tier 3	0.011	0.025	0.016	0.006
	LEV II	0.021	0.039	0.008	0.005
	LEV III	0.011	0.041	0.016	0.014

New average emission factors for aftertreatment (AF) diesel vehicles (Table 2) are also derived from EPA compliance data, in the same manner as described above.

Table 2. Current and Proposed (New) CH_4 and N_2O Emission Factors for Onroad Diesel Vehicles (g/mi)

Class	CH_4		N_2O	
	Current	New	Current	New
LDDV	0.000	0.030	0.001	0.019
LDDT	0.001	0.029	0.001	0.021
HDDV	0.005	0.009	0.005	0.043

Table 1 shows that the proposed (new) emission factors for gasoline cars and trucks are generally lower than what is currently used in the Inventory. Emission factors for diesel cars and trucks with aftertreatment control technology (Table 2) are significantly higher than current values, due to the use of SCR technology on diesel vehicles to achieve lower NOx emissions.

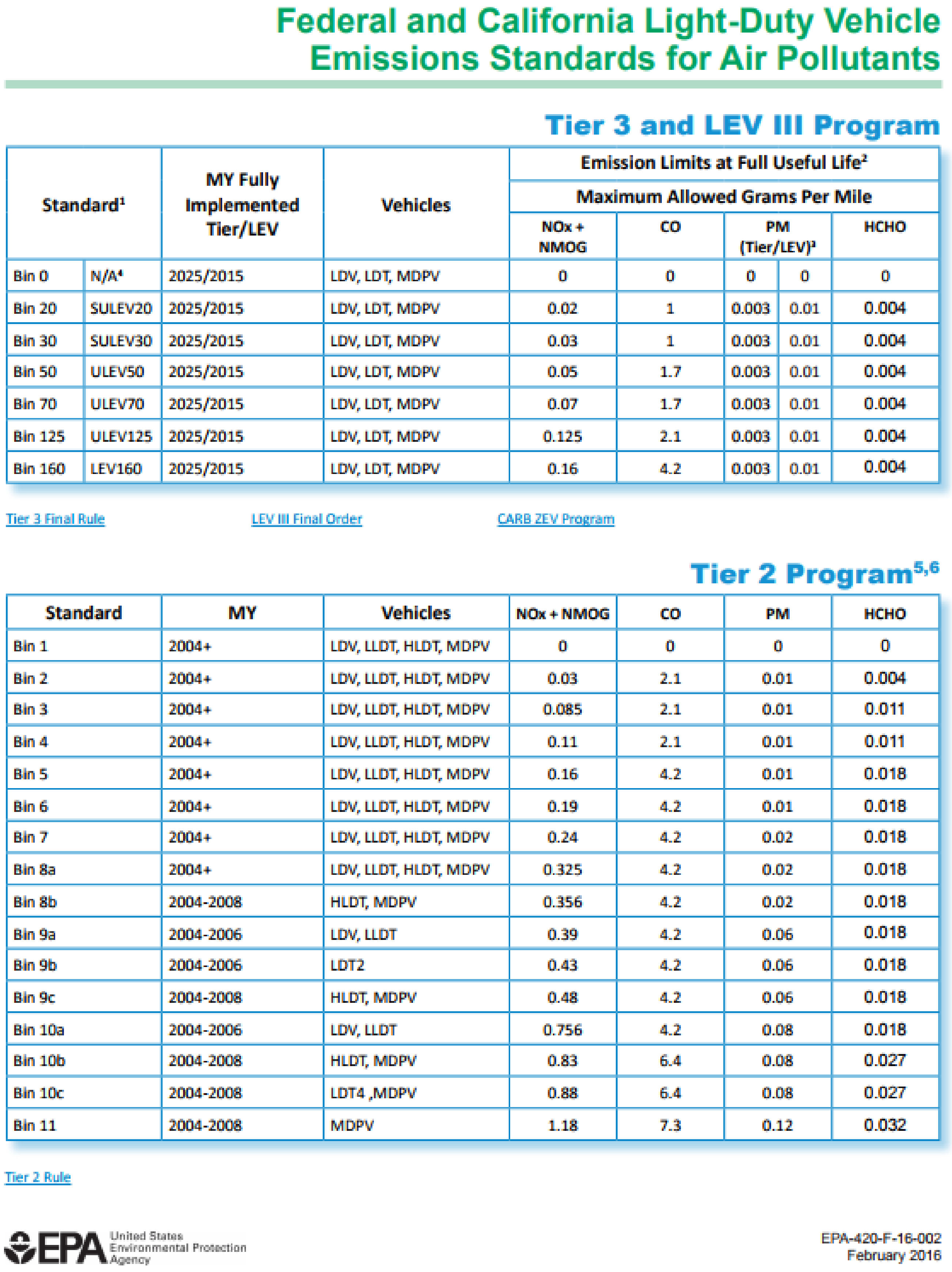
Impacts of the new emission factors are shown in Table 3 in 1000 metric tonnes of emissions for the entire on-highway inventory for calendar years 2016 and 2017.

Table 3. Emission Inventory Impact of Current vs. Proposed (New) CH_4 and N_2O Emission Factors in 1000 Metric Tonnes

	CY 2016				CY 2017			
	CH_4		N_2O		CH_4		N_2O	
Class	**Current**	**New**	**Current**	**New**	**New**	**Current**	**New**	**Current**
LDGV	23.32	23.47	29.90	23.71	21.33	19.19	27.44	20.36
LDGT	8.10	9.24	11.62	9.20	7.26	5.98	10.29	7.68
HDGV	1.41	1.13	1.41	1.14	1.24	1.34	1.31	1.10
LDDV	0.01	0.27	0.01	0.17	0.00	0.28	0.01	0.18
LDDT	0.02	0.51	0.04	0.38	0.02	0.55	0.04	0.41
HDDV	1.33	2.40	1.25	10.75	1.38	2.51	1.30	11.25
Total	**34.19**	**37.02**	**44.22**	**45.36**	**31.24**	**29.85**	**40.38**	**40.98**

As shown in Table 3, the new emission factors result in higher CH_4 and N_2O emissions in CY2016 for most vehicle classes, resulting in greater total CH_4 and N_20 emissions in that year. In CY2017, the updated emission factors result in lower total CH_4 emissions, while total N_2O emissions increase slightly. Much of the increase in N_2O emissions is due to the increase of aftertreatment emission factors for diesel vehicles.

Appendix A
Federal and California Light Duty Vehicle Emission Standards for Air Pollutants



Federal and California Light-Duty Vehicle Emissions Standards for Air Pollutants

Tier 3 and LEV III Program

Standard[1]		MY Fully Implemented Tier/LEV	Vehicles	Emission Limits at Full Useful Life[2] Maximum Allowed Grams Per Mile NOx + NMOG	CO	PM (Tier/LEV)[3]		HCHO
Bin 0	N/A[4]	2025/2015	LDV, LDT, MDPV	0	0	0	0	0
Bin 20	SULEV20	2025/2015	LDV, LDT, MDPV	0.02	1	0.003	0.01	0.004
Bin 30	SULEV30	2025/2015	LDV, LDT, MDPV	0.03	1	0.003	0.01	0.004
Bin 50	ULEV50	2025/2015	LDV, LDT, MDPV	0.05	1.7	0.003	0.01	0.004
Bin 70	ULEV70	2025/2015	LDV, LDT, MDPV	0.07	1.7	0.003	0.01	0.004
Bin 125	ULEV125	2025/2015	LDV, LDT, MDPV	0.125	2.1	0.003	0.01	0.004
Bin 160	LEV160	2025/2015	LDV, LDT, MDPV	0.16	4.2	0.003	0.01	0.004

Tier 3 Final Rule LEV III Final Order CARB ZEV Program

Tier 2 Program[5,6]

Standard	MY	Vehicles	NOx + NMOG	CO	PM	HCHO
Bin 1	2004+	LDV, LLDT, HLDT, MDPV	0	0	0	0
Bin 2	2004+	LDV, LLDT, HLDT, MDPV	0.03	2.1	0.01	0.004
Bin 3	2004+	LDV, LLDT, HLDT, MDPV	0.085	2.1	0.01	0.011
Bin 4	2004+	LDV, LLDT, HLDT, MDPV	0.11	2.1	0.01	0.011
Bin 5	2004+	LDV, LLDT, HLDT, MDPV	0.16	4.2	0.01	0.018
Bin 6	2004+	LDV, LLDT, HLDT, MDPV	0.19	4.2	0.01	0.018
Bin 7	2004+	LDV, LLDT, HLDT, MDPV	0.24	4.2	0.02	0.018
Bin 8a	2004+	LDV, LLDT, HLDT, MDPV	0.325	4.2	0.02	0.018
Bin 8b	2004-2008	HLDT, MDPV	0.356	4.2	0.02	0.018
Bin 9a	2004-2006	LDV, LLDT	0.39	4.2	0.06	0.018
Bin 9b	2004-2006	LDT2	0.43	4.2	0.06	0.018
Bin 9c	2004-2008	HLDT, MDPV	0.48	4.2	0.06	0.018
Bin 10a	2004-2006	LDV, LLDT	0.756	4.2	0.08	0.018
Bin 10b	2004-2008	HLDT, MDPV	0.83	6.4	0.08	0.027
Bin 10c	2004-2008	LDT4 ,MDPV	0.88	6.4	0.08	0.027
Bin 11	2004-2008	MDPV	1.18	7.3	0.12	0.032

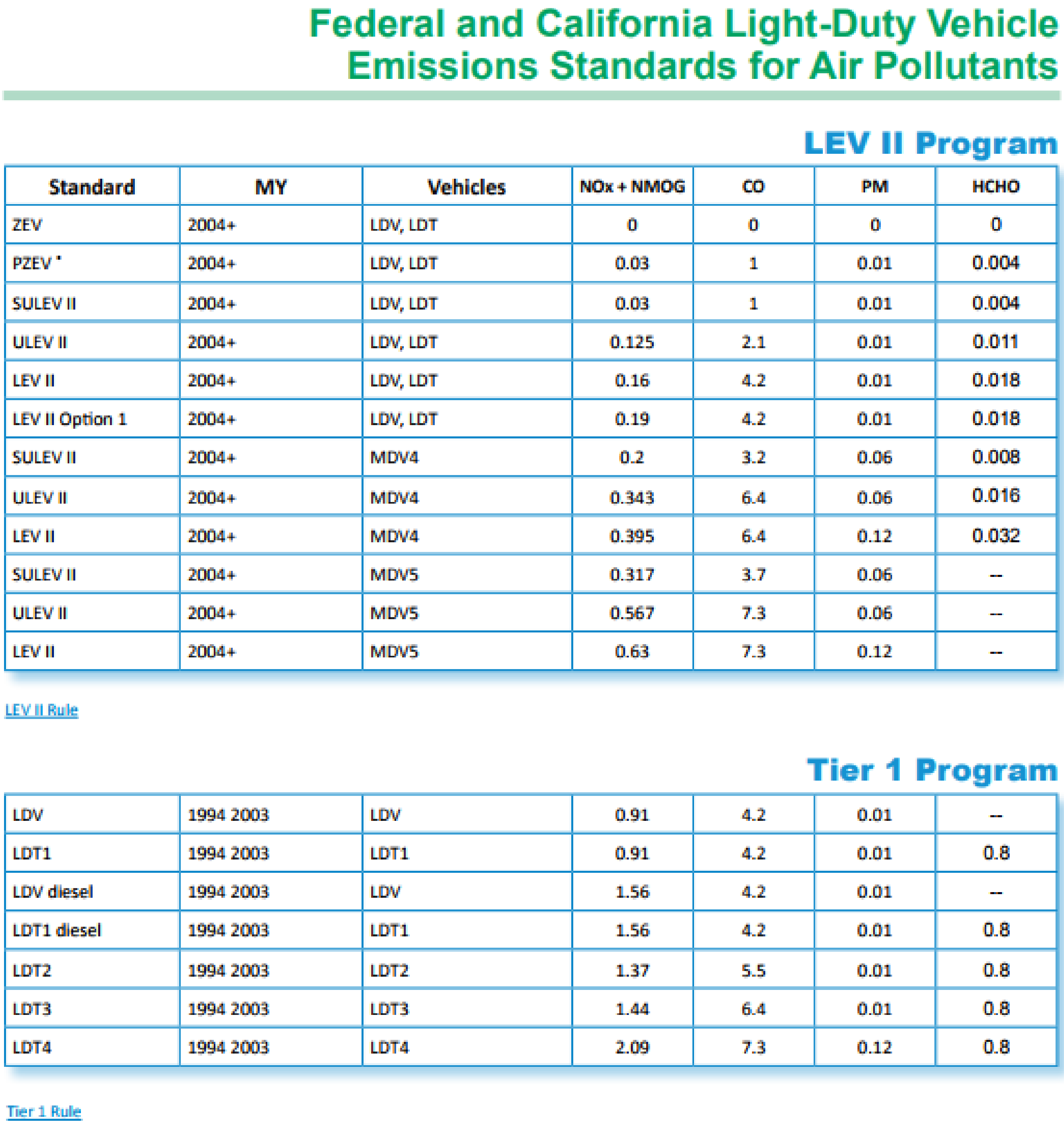
Tier 2 Rule

EPA United States Environmental Protection Agency

EPA-420-F-16-002
February 2016

Appendix A

Federal and California Light Duty Vehicle Emission Standards for Air Pollutants



Federal and California Light-Duty Vehicle Emissions Standards for Air Pollutants

LEV II Program

Standard	MY	Vehicles	NOx + NMOG	CO	PM	HCHO
ZEV	2004+	LDV, LDT	0	0	0	0
PZEV *	2004+	LDV, LDT	0.03	1	0.01	0.004
SULEV II	2004+	LDV, LDT	0.03	1	0.01	0.004
ULEV II	2004+	LDV, LDT	0.125	2.1	0.01	0.011
LEV II	2004+	LDV, LDT	0.16	4.2	0.01	0.018
LEV II Option 1	2004+	LDV, LDT	0.19	4.2	0.01	0.018
SULEV II	2004+	MDV4	0.2	3.2	0.06	0.008
ULEV II	2004+	MDV4	0.343	6.4	0.06	0.016
LEV II	2004+	MDV4	0.395	6.4	0.12	0.032
SULEV II	2004+	MDV5	0.317	3.7	0.06	--
ULEV II	2004+	MDV5	0.567	7.3	0.06	--
LEV II	2004+	MDV5	0.63	7.3	0.12	--

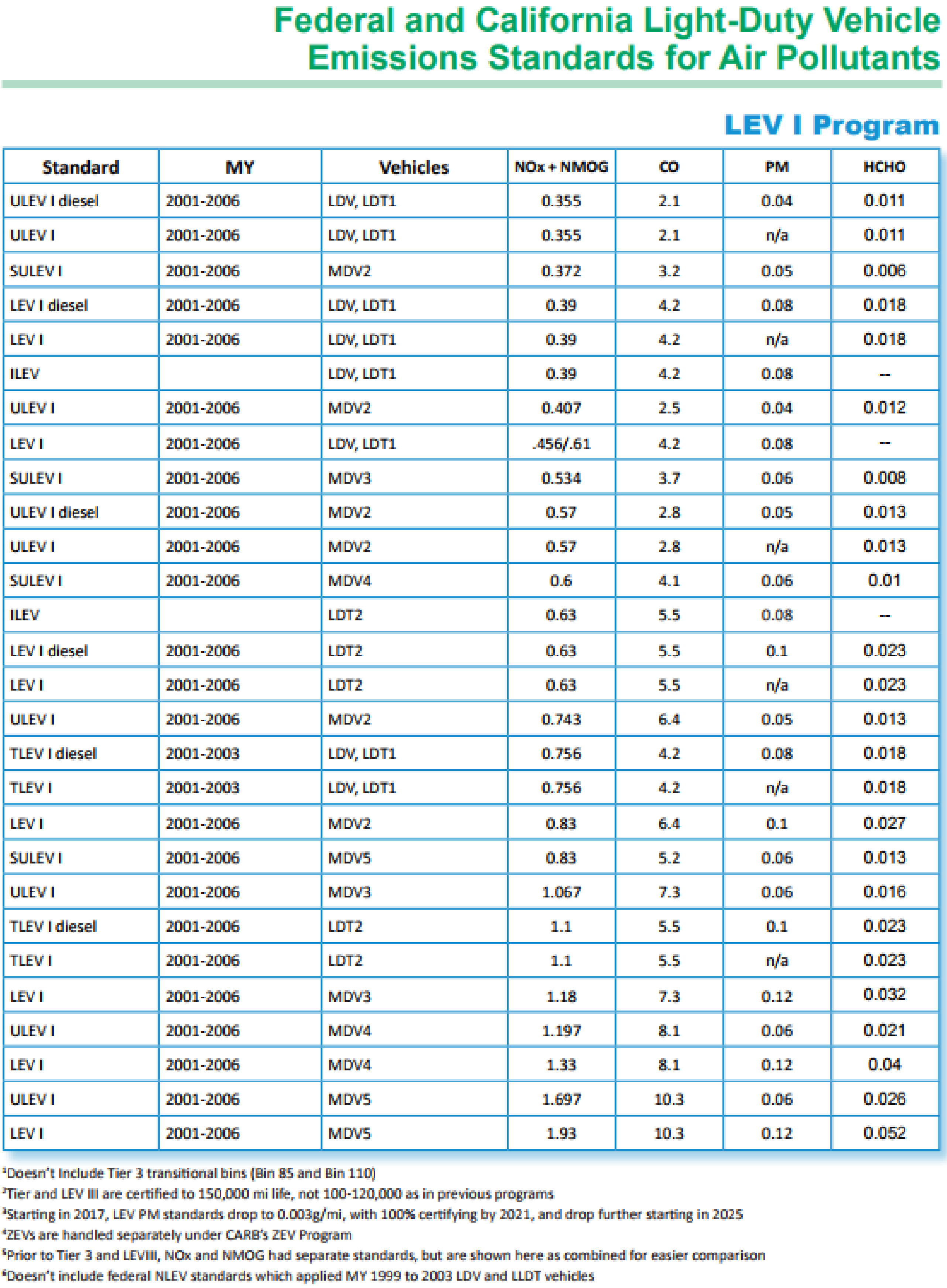
LEV II Rule

Tier 1 Program

LDV	1994 2003	LDV	0.91	4.2	0.01	--
LDT1	1994 2003	LDT1	0.91	4.2	0.01	0.8
LDV diesel	1994 2003	LDV	1.56	4.2	0.01	--
LDT1 diesel	1994 2003	LDT1	1.56	4.2	0.01	0.8
LDT2	1994 2003	LDT2	1.37	5.5	0.01	0.8
LDT3	1994 2003	LDT3	1.44	6.4	0.01	0.8
LDT4	1994 2003	LDT4	2.09	7.3	0.12	0.8

Tier 1 Rule

Appendix A
Federal and California Light Duty Vehicle Emission Standards for Air Pollutants



Federal and California Light-Duty Vehicle Emissions Standards for Air Pollutants

LEV I Program

Standard	MY	Vehicles	NOx + NMOG	CO	PM	HCHO
ULEV I diesel	2001-2006	LDV, LDT1	0.355	2.1	0.04	0.011
ULEV I	2001-2006	LDV, LDT1	0.355	2.1	n/a	0.011
SULEV I	2001-2006	MDV2	0.372	3.2	0.05	0.006
LEV I diesel	2001-2006	LDV, LDT1	0.39	4.2	0.08	0.018
LEV I	2001-2006	LDV, LDT1	0.39	4.2	n/a	0.018
ILEV		LDV, LDT1	0.39	4.2	0.08	--
ULEV I	2001-2006	MDV2	0.407	2.5	0.04	0.012
LEV I	2001-2006	LDV, LDT1	.456/.61	4.2	0.08	--
SULEV I	2001-2006	MDV3	0.534	3.7	0.06	0.008
ULEV I diesel	2001-2006	MDV2	0.57	2.8	0.05	0.013
ULEV I	2001-2006	MDV2	0.57	2.8	n/a	0.013
SULEV I	2001-2006	MDV4	0.6	4.1	0.06	0.01
ILEV		LDT2	0.63	5.5	0.08	--
LEV I diesel	2001-2006	LDT2	0.63	5.5	0.1	0.023
LEV I	2001-2006	LDT2	0.63	5.5	n/a	0.023
ULEV I	2001-2006	MDV2	0.743	6.4	0.05	0.013
TLEV I diesel	2001-2003	LDV, LDT1	0.756	4.2	0.08	0.018
TLEV I	2001-2003	LDV, LDT1	0.756	4.2	n/a	0.018
LEV I	2001-2006	MDV2	0.83	6.4	0.1	0.027
SULEV I	2001-2006	MDV5	0.83	5.2	0.06	0.013
ULEV I	2001-2006	MDV3	1.067	7.3	0.06	0.016
TLEV I diesel	2001-2006	LDT2	1.1	5.5	0.1	0.023
TLEV I	2001-2006	LDT2	1.1	5.5	n/a	0.023
LEV I	2001-2006	MDV3	1.18	7.3	0.12	0.032
ULEV I	2001-2006	MDV4	1.197	8.1	0.06	0.021
LEV I	2001-2006	MDV4	1.33	8.1	0.12	0.04
ULEV I	2001-2006	MDV5	1.697	10.3	0.06	0.026
LEV I	2001-2006	MDV5	1.93	10.3	0.12	0.052

[1] Doesn't Include Tier 3 transitional bins (Bin 85 and Bin 110)

[2] Tier and LEV III are certified to 150,000 mi life, not 100-120,000 as in previous programs

[3] Starting in 2017, LEV PM standards drop to 0.003g/mi, with 100% certifying by 2021, and drop further starting in 2025

[4] ZEVs are handled separately under CARB's ZEV Program

[5] Prior to Tier 3 and LEVIII, NOx and NMOG had separate standards, but are shown here as combined for easier comparison

[6] Doesn't include federal NLEV standards which applied MY 1999 to 2003 LDV and LLDT vehicles

Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Updated Gasoline CO_2 Emission Factors

This memo provides research and analyses to support improvements in the U.S. Greenhouse Gas Inventory. Updated gasoline carbon factors are estimated.

Summary

This memo details suggested changes to the gasoline carbon factors used in the U.S. Greenhouse Gas Inventory.

- **Current Method –** The current inventory lists NIPER (1990 through 2009) data[1] to determine gasoline composition. NIPER has ceased to exist and the referenced reports are out of circulation. Current C factors have not been updated since 2010 (for the 1990-2008 Inventory Report).
- **Proposed Method –** New data are available in publications after 2009, including historic data, which can be used to calculate new gasoline carbon factors. It is proposed to use this data to develop gasoline carbon factors for years after 2008 and update carbon factors from 1990 to 2008.
- **Charge Questions –** There are charge questions related to the proposed method provided at the end of the memo to help focus the review (see p.12)

Background

The current GHG inventory calculates grams of carbon dioxide (CO_2) emitted from gasoline consumption based upon the gallons of fuel used. A conversion factor is used to convert gallons into quadrillion Btus (QBtu) and another factor is used to compute CO_2 emissions from gasoline energy use. This latter factor provides million metric tonnes (MMT) of carbon (C) per QBtu of gasoline and is based upon the density, higher heating value and carbon content of the fuel. Once the amount of carbon is calculated, the amount of CO_2 generated can be estimated by the ratio of the molecular weights of CO_2 and C.

The National Institute for Petroleum and Energy Research (NIPER) compiled properties of summer and winter gasolines from 1990 to 2009[1]. These were used to determine the component composition of different gasolines. The NIPER data along with assumed C contents of the different components were used to compute the carbon fraction assumed in the Inventory. Since that time the C factor has not been updated to reflect current gasolines properties.

The proposed updated approach described here relies on a number of new data sources. The Energy Information Administration (EIA) publishes prime supplier sales volumes of motor gasoline by type (conventional, oxygenated, and reformulated) and by grade (regular, midgrade

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[1] National Institute for Petroleum and Energy Research (NIPER) (1990 through 2009) Motor Gasolines, Summer and Motor Gasolines, Winter.

and premium) for each month from 1983 to present.[2] EPA publishes a breakdown of conventional and reformulated gasoline in their Trends report[3] which gives volumes of gasoline components (aromatics, benzene, oxygenates and olefins) by gasoline type (conventional and reformulated) and season (winter and summer), for fuels sold outside of California, for 1997-2016. Finally, the American Petroleum Institute (API) provided sample non-oxygenated compositions of both winter and summer gasolines[4] that can be used to determine C contents of different gasoline components. The combination of these sources was used to determine an updated C factor for gasoline over the time series of the Inventory.

Assumptions

The EPA Trends report is assumed to provide a representative mix of components in the different types of gasoline sold. The breakdown of compounds within the saturated, aromatic and olefin components in the API data are assumed to be similar enough to the gasolines being produced over time and across grades. These assumptions are discussed below and further outlined as part of Charge Questions at the end of this memo.

Calculations

Using the monthly sales of gasoline from EIA, annual totals of conventional, oxygenated and reformulated gasoline is determined for both summer and winter. Gasoline sold in May – Aug was assumed to be summer grade, gasoline sold in September was assumed to be half summer and half winter grade, and gasoline sold in other months was assumed to be winter grade. The amount of ethanol within each gasoline is removed as ethanol is treated separately in the inventory. Total volumes of non-ethanol gasoline sales are shown in Table 1.

Table 1. Non-Ethanol Gasoline Sales in 1000 bbls

Calendar Year	Conventional		Oxygenated		Reformulated	
	Winter	Summer	Winter	Summer	Winter	Summer
1990	1,587,068	1,035,872	0	0	0	0
1991	1,589,226	1,013,590	0	0	0	0
1992	1,627,363	1,009,097	0	0	0	0
1993	1,658,914	1,042,531	0	0	0	0
1994	1,344,579	1,049,013	266,828	11,522	71,868	0
1995	1,145,737	800,856	114,774	11,405	451,519	285,645
1996	1,157,119	751,545	77,268	14,110	518,768	345,532
1997	1,138,680	748,390	62,703	19,205	568,670	358,602
1998	1,145,856	753,870	74,768	29,868	596,512	378,586
1999	1,180,808	766,023	77,526	29,788	605,392	383,353
2000	1,157,251	768,017	79,075	35,245	627,127	394,692
2001	1,173,842	776,007	79,489	34,018	639,032	398,828
2002	1,200,769	794,617	78,780	35,323	658,380	412,230

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[2] EIA, *Prime Supplier Sales Volume* at https://www.eia.gov/dnav/pet/pet_cons_prim_dcu_nus_m.htm

[3] EPA, *Gasoline Properties Over Time* at https://www.epa.gov/fuels-registration-reporting-and-compliance-help/gasoline-properties-over-time

[4] https://www.api.org/~/media/Files/Policy/Fuels-and-Renewables/2016-Oct-RFS/The-Truth-About-E15/E10-Blending-Study-Final-Report.pdf

Calendar Year	Conventional		Oxygenated		Reformulated	
	Winter	Summer	Winter	Summer	Winter	Summer
2003	1,205,428	799,970	78,803	37,278	655,751	416,721
2004	1,254,363	813,280	74,362	33,279	664,195	408,525
2005	1,237,444	809,139	71,579	35,752	668,202	424,381
2006	1,285,904	834,180	71,823	35,189	641,003	378,570
2007	1,352,219	861,717	0	0	623,224	388,163
2008	1,271,936	781,475	0	0	627,781	378,309
2009	1,224,432	787,366	0	0	622,290	386,866
2010	1,198,796	772,241	0	0	615,419	389,707
2011	1,161,169	733,142	0	0	615,060	378,399
2012	1,160,682	735,152	0	0	600,701	374,440
2013	1,179,391	744,877	0	0	606,171	382,592
2014	1,191,305	752,585	0	0	612,322	379,800
2015	1,209,040	769,418	0	0	639,065	400,519
2016	1,226,520	781,341	0	0	651,325	409,047
2017	1,237,358	795,119	0	0	628,616	398,210
2018	1,238,651	798,821	0	0	627,931	393,685

Next, the density of non-ethanol conventional and reformulated gasoline is calculated from the EPA Trends data. Gasoline density (including ethanol) is calculated based on API gravity using the following formula:

$$\rho_g = 141.5 / (API + 131.5) \times \rho_w$$

Where:

ρ_g = density of gasoline (kg/gallon)

API = API gravity (annual data from the EPA Trends report as shown in Annex 1)

ρ_w = density of water, 3.785 kg/gallon

Finally the ethanol component is removed and density adjusted using the following formula:

$$P_{neg} = (\rho_g - EV \times \rho_e) / (1-EV)$$

Where:

ρ_{neg} = density of non-ethanol gasoline (kg/gallon)

ρ_g = density of gasoline (kg/gallon)

EV = ethanol volume percent

ρ_e = density of ethanol, 2.988 kg/gallon

This provides the densities shown in Table 2.

Table 2. Non-Ethanol Gasoline Densities (kg/gallon)

Calendar Year	Non-Ethanol Gasoline Densities			
	Conventional		Reformulated	
	Winter	Summer	Winter	Summer
1997	2.778	2.823	2.758	2.825
1998	2.774	2.824	2.766	2.826
1999	2.775	2.822	2.766	2.823
2000	2.774	2.830	2.760	2.811

Calendar Year	Non-Ethanol Gasoline Densities			
	Conventional		Reformulated	
	Winter	Summer	Winter	Summer
2001	2.783	2.833	2.763	2.817
2002	2.780	2.830	2.762	2.817
2003	2.784	2.836	2.763	2.815
2004	2.767	2.823	2.762	2.818
2005	2.765	2.818	2.763	2.815
2006	2.767	2.823	2.763	2.816
2007	2.762	2.821	2.756	2.806
2008	2.753	2.801	2.746	2.795
2009	2.755	2.806	2.749	2.805
2010	2.751	2.798	2.749	2.801
2011	2.748	2.792	2.738	2.800
2012	2.741	2.787	2.735	2.790
2013	2.737	2.784	2.729	2.787
2014	2.735	2.781	2.724	2.783
2015	2.778	2.823	2.758	2.825
2016	2.774	2.824	2.766	2.826

Quantities sold of non-ethanol conventional and reformulated gasoline are then divided into components (MTBE, TAME, Benzene, non-Benzene Aromatics, Olefins and Saturates) using the EPA Trends report (see Annex 1). Winter and summer grades of conventional gasoline are shown in Tables 3 and 4, respectively and winter and summer grades of reformulated gasoline are shown in Tables 5 and 6, respectively. Note that the EPA Trends report only provides gasoline component breakdowns for 1997 through 2016.

Table 3. Winter Grade Conventional Gasoline Sales

Calendar Year	Volume (1000 bbls)					
	MTBE	TAME	Aromatics*	Benzene	Olefins	Saturates
1997	6,780	295	234,355	11,300	119,880	609,715
1998	21,672	2,530	259,848	11,881	123,213	672,063
1999	20,139	1,245	269,495	12,219	128,977	688,106
2000	15,984	1,725	272,763	12,419	137,991	695,362
2001	17,994	2,220	283,467	13,320	146,057	690,906
2002	16,337	3,196	283,286	12,667	139,690	714,429
2003	17,138	2,057	271,915	12,568	131,388	690,527
2004	21,125	2,158	267,126	12,266	129,474	681,556
2005	16,058	2,050	268,201	13,097	132,107	682,403
2006	2,037	113	266,315	13,242	125,631	719,039
2007	339	0	261,386	12,985	125,330	714,266
2008	103	0	222,640	12,043	107,048	646,921
2009	0	0	218,490	11,610	102,394	647,415
2010	0	0	213,749	10,351	100,738	653,945
2011	0	0	226,292	8,451	107,864	732,398
2012	0	0	209,780	7,428	99,038	709,920
2013	0	0	208,149	6,938	101,993	734,533
2014	0	0	208,951	7,001	102,874	760,102
2015	0	0	212,584	7,042	99,190	764,036
2016	0	0	216,744	6,900	96,595	756,345

Table 4. Summer Grade Conventional Gasoline Sales

Calendar Year	Volume (1000 bbls)					
	MTBE	TAME	Aromatics*	Benzene	Olefins	Saturates
1997	9,949	553	240,154	10,409	115,149	544,055
1998	17,768	2,140	244,293	10,605	106,983	543,008
1999	16,817	1,208	245,746	10,685	109,633	537,203
2000	14,757	2,186	249,139	10,476	107,490	519,229
2001	16,062	2,600	251,889	10,863	118,842	521,326
2002	16,803	3,302	261,276	10,684	117,526	552,662
2003	22,506	2,374	276,162	11,872	124,918	584,431
2004	22,440	2,049	275,123	11,784	114,763	582,933
2005	16,166	1,850	257,981	11,784	116,866	552,191
2006	321	0	292,751	13,044	120,821	637,572
2007	105	0	284,431	12,876	116,201	619,739
2008	0	0	230,186	11,183	97,853	555,709
2009	0	0	227,233	10,613	98,550	552,259
2010	0	0	216,352	9,757	90,913	543,883
2011	0	0	212,657	7,602	92,294	580,371
2012	0	0	213,146	6,901	95,420	596,928
2013	0	0	204,817	6,385	92,339	589,498
2014	0	0	205,022	6,382	92,639	601,306
2015	0	0	213,699	6,451	92,053	616,727
2016	0	0	210,595	6,297	83,758	603,498

Table 5. Winter Grade Reformulated Gasoline Sales

Calendar Year	Volume (1000 bbls)					
	MTBE	TAME	Aromatics*	Benzene	Olefins	Saturates
1997	30,738	2,532	65,344	2,180	40,444	206,583
1998	31,763	2,523	68,037	2,309	38,726	207,807
1999	30,587	2,925	68,432	2,347	40,806	211,760
2000	31,180	2,810	69,691	2,469	44,815	224,188
2001	31,190	2,715	69,998	2,414	46,389	219,987
2002	31,344	2,309	73,410	2,504	43,435	233,181
2003	30,815	1,509	74,495	2,541	43,680	237,384
2004	28,805	1,352	75,679	2,581	45,481	244,859
2005	27,401	1,199	77,863	2,728	46,288	245,988
2006	14,366	41	77,998	2,732	44,712	245,336
2007	41	0	75,301	2,639	45,774	248,748
2008	0	0	74,249	2,709	46,002	265,481
2009	0	0	72,692	2,727	44,740	264,818
2010	0	0	71,387	2,638	46,372	263,851
2011	0	0	66,292	2,400	44,691	260,410
2012	0	0	64,164	2,157	41,950	252,779
2013	0	0	62,938	2,033	41,454	253,666
2014	0	0	65,558	2,203	40,740	266,972
2015	0	0	67,810	2,265	40,806	274,958
2016	0	0	69,254	2,223	39,922	282,071

Table 6. Summer Grade Reformulated Gasoline Sales

Calendar Year	Volume (1000 bbls)					
	MTBE	TAME	Aromatics*	Benzene	Olefins	Saturates
1997	26,197	2,349	65,538	1,963	36,575	161,911
1998	26,197	2,349	65,538	1,963	36,575	161,911
1999	27,050	2,398	66,882	2,034	33,395	168,738
2000	26,760	2,676	66,870	2,209	35,473	173,849
2001	28,125	2,956	58,210	1,836	32,979	183,467
2002	28,441	2,838	61,422	1,955	37,207	179,979
2003	29,520	2,507	65,340	1,946	35,622	190,611
2004	28,839	2,686	63,083	1,974	35,603	186,626
2005	25,122	1,422	66,055	1,998	38,597	195,085
2006	22,686	1,487	64,763	2,133	38,457	183,850
2007	508	0	62,000	1,875	34,956	188,224
2008	33	0	61,716	1,858	37,819	193,365
2009	0	0	57,676	1,844	35,259	197,676
2010	0	0	59,516	1,837	37,075	198,202
2011	0	0	59,949	1,892	37,848	205,731
2012	0	0	56,535	1,739	38,634	194,105
2013	0	0	53,322	1,559	37,670	201,013
2014	0	0	51,586	1,531	34,682	194,689
2015	0	0	52,777	1,547	36,545	206,827
2016	0	0	56,599	1,635	37,120	212,468

* Aromatics listed in Tables 3-6 are non-benzene aromatics

Next, the carbon content of each of the various components of summer and winter gasolines is determined based on the API data. Table 7 shows a comparison between the ranges of Aromatics, Olefins and Saturates data in Conventional and Reformulated gasolines from the EPA Trends report and the totals of those components from the API data for the different grades of gasoline. The API data was just used to determine the carbon fraction of winter and summer gasoline components (non-benzene aromatics, olefins and saturates). As can be seen by Table 7, the API data is a reasonable representation of both winter and summer gasolines.

Table 7. Comparison of API data versus EPA Trends data

Component	Winter Grade			Summer Grade		
	Conventional	Reformulated	API	Conventional	Reformulated	API
Aromatics	20.0%-26.2%	18.0%-22.2%	19.1%	23.4%-29.3%	18.2%-25.4%	36.1%
Olefins	9.0%-12.9%	10.1%-13.7%	11.0%	9.3%-13.2%	11.6%-13.8%	10.5%
Saturates	60.9%-70.6%	64.9%-71.7%	69.9%	57.7%-66.7%	60.9%-69.5%	53.4%

Table 8 shows the breakdown of saturated hydrocarbons in summer and winter gasolines and the carbon fraction for each compound based on the API data. Carbon fraction is calculated using a molecular weight of C of 12.0107, molecular weight of H of 1.0079, and molecular weight of O of 15.9994. A similar procedure was done for non-benzene aromatics (Table 9) and olefins (Table 10). Annex 2 describes how the speciated component lists of different grades of gasoline (shown in Tables 8-10) were developed using the API data.

Table 8. Saturated Hydrocarbon Carbon Fraction

Compound	Formula	C	H	Carbon (mass %)	Volume Percent	
					Winter	Summer
n-Butane	C4H10	4	10	82.7%	14.9%	7.1%
n-Pentane	C5H12	5	12	83.2%	7.7%	5.2%
n-Hexane	C6H14	6	14	83.6%	3.1%	3.0%
n-Heptane	C7H16	7	16	83.9%	1.4%	1.3%
n-Octane	C8H18	8	18	84.1%	3.4%	1.7%
n-Nonane	C9H20	9	20	84.3%	3.3%	0.4%
n-Decane	C10H22	10	22	84.4%	2.1%	0.4%
Isobutane	C4H10	4	10	82.7%	0.3%	1.3%
Isopentane	C5H12	5	12	83.2%	13.6%	12.9%
2M-Pentane	C6H14	6	14	83.6%	10.6%	8.4%
3M-Hexane	C7H16	7	16	83.9%	4.9%	5.1%
3M-Heptane	C8H18	8	18	84.1%	4.0%	3.4%
23DM-Butane	C6H14	6	14	83.6%	2.4%	4.3%
24DM-Pentane	C7H16	7	16	83.9%	1.0%	2.4%
23DM-Hexane	C8H18	8	18	84.1%	3.6%	5.8%
224TM-Pentane	C8H18	8	18	84.1%	18.6%	33.0%
225TM-Hexane	C9H20	9	20	84.3%	1.1%	2.4%
3M Octane	C9H20	9	20	84.3%	3.1%	0.7%
226TM Octane	C11H24	11	24	84.5%	0.9%	1.1%
Saturated Hydrocarbon Weighted Carbon Percent					83.6%	83.9%

Table 9. Non-Benzene Aromatics Carbon Fraction

Compound	Formula	C	H	Carbon (mass %)	Volume Percent	
					Winter	Summer
Toluene	C7H8	7	8	91.2%	13.4%	33.5%
Xylene	C8H10	8	10	90.5%	26.2%	17.6%
1,2M, 4E-Benzene	C10H14	10	14	89.5%	7.5%	5.0%
1M3E-Benzene	C9H12	9	12	89.9%	13.4%	14.2%
123TM-Benzene	C9H12	9	12	89.9%	18.2%	22.3%
Cyclopentane	C5H10	5	10	85.6%	2.1%	0.8%
Cyclohexane	C6H12	6	12	85.6%	1.6%	0.6%
M-Cyclopentane	C6H12	6	12	85.6%	9.1%	3.4%
M-Cyclohexane	C7H14	7	14	85.6%	3.2%	0.8%
DM-Cyclopentane	C7H14	7	14	85.6%	5.3%	1.7%
Non-Benzene Aromatics Weighted Carbon Percent					89.3%	90.1%

Table 10. Olefin Carbon Fraction

Compound	Formula	C	H	Carbon (mass %)	Volume Percent	
					Winter	Summer
2M-2-Butene	C5H10	5	10	85.6%	24.5%	22.9%
1-Pentene	C5H10	5	10	85.6%	34.5%	50.5%
1-Hexene	C6H12	6	12	85.6%	40.9%	26.7%
Olefin Weighted Carbon Percent					85.6%	85.6%

Table 11 gives the final carbon fractions for the non-ethanol components of gasoline using the weighted averages from Tables 8 through 10. Carbon fractions for MTBE, TAME, and benzene are calculated based on their chemical formula.

Table 11. Gasoline Component Carbon Fraction

Compound	Carbon (mass %)	
	Winter	Summer
MTBE	68.1%	68.1%
TAME	70.5%	70.5%
Non-Benzene Aromatics	89.3%	90.1%
Benzene	92.3%	92.3%
Olefins	85.6%	85.6%
Saturates	83.6%	83.8%

Using the fuel volume information in Tables 3-6 and carbon fraction information from Table 11, weighted average carbon percent is estimated (Table 12).

Table 12. Weighted Average Non-Ethanol Gasoline Carbon Mass Percent

Calendar Year	Non-Ethanol Gasoline Carbon Mass Percent			
	Conventional		Reformulated	
	Winter	Summer	Winter	Summer
1997	85.2%	85.6%	83.5%	84.0%
1998	85.0%	85.4%	83.5%	83.9%
1999	85.0%	85.5%	83.6%	83.9%
2000	85.1%	85.5%	83.6%	83.7%
2001	85.1%	85.5%	83.6%	83.7%
2002	85.1%	85.5%	83.7%	83.8%
2003	85.1%	85.4%	83.7%	83.8%
2004	85.0%	85.4%	83.8%	84.1%
2005	85.1%	85.5%	83.9%	84.2%
2006	85.3%	85.8%	84.5%	85.4%
2007	85.3%	85.8%	85.1%	85.4%
2008	85.2%	85.7%	85.0%	85.3%
2009	85.2%	85.7%	85.0%	85.3%
2010	85.2%	85.7%	85.0%	85.3%
2011	85.1%	85.5%	84.9%	85.3%
2012	85.1%	85.5%	84.9%	85.2%
2013	85.0%	85.5%	84.9%	85.2%
2014	85.0%	85.4%	84.9%	85.2%
2015	85.0%	85.5%	84.9%	85.2%
2016	85.0%	85.5%	84.9%	85.2%

Next, the densities in Table 2 are combined with the carbon mass weight percent in Table 12 to produce carbon weight per barrel of fuel (Table 13). Note that a barrel of fuel is 42 gallons.

Table 13. Non-Ethanol Gasoline Carbon Fractions (kg/bbl)

Calendar Year	Non-Ethanol Gasoline C Fractions			
	Conventional		Reformulated	
	Winter	Summer	Winter	Summer
1997	99.44	101.48	96.77	99.63
1998	98.98	101.32	97.01	99.63
1999	99.09	101.32	97.07	99.54
2000	99.15	101.67	96.89	98.77
2001	99.48	101.77	97.02	99.09

Calendar Year	Non-Ethanol Gasoline C Fractions			
	Conventional		Reformulated	
	Winter	Summer	Winter	Summer
2002	99.35	101.60	97.06	99.11
2003	99.47	101.74	97.15	99.02
2004	98.78	101.28	97.25	99.50
2005	98.81	101.20	97.40	99.52
2006	99.10	101.75	98.04	100.99
2007	98.95	101.70	98.48	100.63
2008	98.56	100.84	98.06	100.11
2009	98.59	101.01	98.15	100.50
2010	98.42	100.64	98.14	100.34
2011	98.22	100.32	97.68	100.29
2012	97.90	100.08	97.57	99.83
2013	97.72	99.95	97.31	99.71
2014	97.63	99.80	97.13	99.55
2015	97.64	99.82	97.13	99.59
2016	97.66	99.83	97.12	99.59

Next, the higher heating value of non-ethanol gasoline is calculated based upon the energy content of gasoline blendstock and non-ethanol oxygenates per EIA data[5] and the composition of the non-ethanol portion of the gasoline by type, season, and grade. Non-ethanol blendstock higher heating value is 5.253 mmBtu/bbl through 2006 and 5.222 mmBtu/bbl after 2006. The higher heating value of non-ethanol oxygenates is 4.247 mmBtu/bbl. Taking into account the percent of non-ethanol oxygenates in the gasoline and the remaining gasoline blendstock, Table 14 shows the higher heating value for non-ethanol gasoline.

Table 14. Non-Ethanol Gasoline Higher Heating Value (mmBtu/bbl)

Calendar Year	Conventional		Oxygenated		Reformulated	
	Winter	Summer	Winter	Summer	Winter	Summer
1990	5.253	5.253	5.253	5.253	5.253	5.253
1991	5.253	5.253	5.253	5.253	5.253	5.253
1992	5.253	5.253	5.253	5.253	5.253	5.253
1993	5.238	5.229	5.253	5.253	5.253	5.253
1994	5.233	5.227	5.253	5.253	5.253	5.253
1995	5.247	5.245	5.250	5.238	5.158	5.157
1996	5.248	5.244	5.248	5.241	5.171	5.174
1997	5.247	5.243	5.247	5.243	5.171	5.171
1998	5.238	5.239	5.238	5.239	5.188	5.187
1999	5.239	5.238	5.239	5.238	5.183	5.182
2000	5.242	5.240	5.242	5.240	5.188	5.181
2001	5.241	5.240	5.241	5.240	5.192	5.186
2002	5.242	5.239	5.242	5.239	5.194	5.186
2003	5.244	5.241	5.244	5.241	5.211	5.203
2004	5.245	5.244	5.245	5.244	5.225	5.223
2005	5.247	5.247	5.247	5.247	5.228	5.226
2006	5.252	5.253	5.252	5.253	5.237	5.252
2007	5.221	5.222	5.222	5.222	5.222	5.222

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[5] EIA, *Monthly Energy Review, Appendix A* at https://www.eia.gov/totalenergy/data/monthly/pdf/sec12_2.pdf

Calendar Year	Conventional		Oxygenated		Reformulated	
	Winter	Summer	Winter	Summer	Winter	Summer
2008	5.222	5.222	5.222	5.222	5.222	5.222
2009	5.222	5.222	5.222	5.222	5.222	5.222
2010	5.221	5.222	5.222	5.222	5.222	5.222
2011	5.221	5.222	5.222	5.222	5.222	5.222
2012	5.221	5.222	5.222	5.222	5.222	5.222
2013	5.221	5.222	5.222	5.222	5.222	5.222
2014	5.221	5.222	5.222	5.222	5.222	5.222
2015	5.221	5.222	5.222	5.222	5.222	5.222
2016	5.221	5.222	5.222	5.222	5.222	5.222
2017	5.222	5.222	5.222	5.222	5.222	5.222
2018	5.222	5.222	5.222	5.222	5.222	5.222

Using the fuel sales in Table 1, the carbon fractions in Table 13, and the higher heating values in Table 14, carbon fractions in terms of million metric tonnes (MMT) per quadrillion Btu (QBtu) are shown in Table 15. These values are compared with the values currently used in the Inventory. Carbon fractions for 1990 through 1996 were assumed to be the same as those for 1997 and carbon fractions for 2017 through 2018 were assumed to be the same as those for 2016. Going forward, data would be updated as new composition data becomes available. As shown in Table 15, the new values are 1.4% to 3.2% lower than the current values.

Table 15. Non-Ethanol Gasoline Carbon Factor (MMT/QBtu)

Calendar Year	New	Current	New vs current
1990	19.11	19.42	-1.6%
1991	19.11	19.44	-1.7%
1992	19.10	19.49	-2.0%
1993	19.11	19.44	-1.7%
1994	19.10	19.36	-1.4%
1995	19.06	19.36	-1.5%
1996	19.05	19.35	-1.6%
1997	19.05	19.36	-1.6%
1998	19.01	19.37	-1.8%
1999	19.03	19.32	-1.5%
2000	19.01	19.33	-1.6%
2001	19.05	19.34	-1.5%
2002	19.03	19.38	-1.8%
2003	19.03	19.36	-1.7%
2004	18.94	19.38	-2.3%
2005	18.94	19.36	-2.2%
2006	19.02	19.45	-2.3%
2007	19.11	19.56	-2.3%
2008	19.00	19.46	-2.3%
2009	19.03	19.46	-2.2%
2010	19.00	19.46	-2.4%
2011	18.94	19.46	-2.6%
2012	18.89	19.46	-2.9%
2013	18.86	19.46	-3.1%
2014	18.83	19.46	-3.2%

Calendar Year	New	Current	New vs current
2015	18.83	19.46	-3.2%
2016	18.84	19.46	-3.2%
2017	18.84	19.46	-3.2%
2018	18.84	19.46	-3.2%

There are a number of elements in the calculations that lead to the differences in the new vs. current factors shown above in Table 15 including:

- Use of the EPA Trends data to represent gasoline MTBE, TAME, Benzene, non-Benzene Aromatics, Olefins and Saturates composition as opposed to the historic NIPER data.
- Basing carbon content of the different gasoline components on the API data as opposed to basing it on assumed representative molecules which resulted in lower assumed carbon fractions. This only impacts non-Benzene Aromatics and Saturates carbon content assumptions[6]. The differences are shown in Table 16.

Table 16. Comparison of Gasoline Component Carbon Fractions

Compound	Carbon (mass %)		
	Current	API Winter	API Summer
Non-Benzene Aromatics	91.25% (based on toluene)	89.31%	90.14%
Saturates	84.12% (based on octane)	83.64%	83.75%

- Updated heating values. The current approach assumed standard heat contents for motor gasoline of 5.222 mmBtu/bbl for conventional gasoline and 5.150 mmBtu/bbl for reformulated gasoline across the time series. The updated approach, as discussed above, assumes a non-ethanol higher heating value of 5.253 mmBtu/bbl through 2006 and 5.222 mmBtu/bbl after 2006 for both conventional and reformulated gasoline. It also factors in the higher heating value of non-ethanol oxygenates of 4.247 mmBtu/bbl. The update results in increasing the assumed heating value of gasoline by roughly 0.5% across time. An increase in the assumed heating value results in a lower carbon factor per heat content.

Preliminary estimates indicate that incorporating the new carbon factors in the inventory would result in lowering the annual emission estimates by an average of 24.7 MMT CO_2 per year across the time series. This represents an average decrease in petroleum CO_2 emissions across all sectors of 1.1% per year and a decrease in total fossil fuel combustion CO_2 emissions of 0.5% per year. The overall historic and cross-sector contribution trends would not generally be impacted.

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[6] The carbon contents of other components are based on molecular formula and did not change. All olefins have the same carbon share because they all have a molecular formula in the form CnH2n so the carbon content is the same in existing vs. updated calculations.

Charge Questions

Gasoline Component Composition:

1. Is the EPA Trends data a good data source for determining gasoline composition? Are there other sources available, including for the full time series 1990-2018 and going forward?
2. Is it reasonable to apply the EPA Trends data across all fuel types (i.e., California fuels not included)?
3. Should the EPA Trends data be used for the full time series or just for years where the NIPER data is not available?
4. If using across the time series, is it reasonable to apply the 1997 results to 1990-1996 and the 2016 results to 2017-2018?

Component Speciation:

1. Is it reasonable to use the API data to speciate gasoline components?
2. Is the approach outlined in Annex 2 of this memo to develop the gasoline speciated components reasonable (see p. 15)?
3. Is the API data representative of different gasoline types? If not, is there a better approach to use?
4. Is the API data representative over time? If not is there a better approach?
5. Are there other gasoline speciation data available?
6. Would it be better to use a representative molecule to represent carbon content of different gasoline components?

Carbon Factor:

1. The carbon factor of each gasoline component is based on a percent by mass and are distributed across the full fuel based on the density of the entire gallon. Should individual densities be used instead? If so is there a good source of data for these densities?
2. The carbon factors are lower than what was found previously; do the updated values seem reasonable?

Heating Value:

1. Is the approach for developing heating values reasonable?
2. Are there other data sources available on heating content?
3. The factor is slightly higher than current factors used; do the update seem reasonable?

Annex 1: EPA Trends Data

Conventional Gasoline:

Year	Volume	Oxygen	API	Ethanol	MTBE	TAME	Aromatics (non-benzene)	Benzene	Olefins	Saturates
	Million Gallons	Wt%	Gravity	Vol%	Vol%	Vol%	Vol%	Vol%	Vol%	Vol%
Winter										
1997	41,270	0.19	61.3	0.03	0.69	0.03	23.85	1.15	12.2	62.05
1998	46,205	0.72	61.5	0.81	1.97	0.23	23.62	1.08	11.2	61.09
1999	47,518	0.74	61.4	0.99	1.78	0.11	23.82	1.08	11.4	60.82
2000	48,297	0.74	61.4	1.19	1.39	0.15	23.72	1.08	12	60.47
2001	49,075	0.77	60.8	1.24	1.54	0.19	24.26	1.14	12.5	59.13
2002	49,720	0.73	61	1.2	1.38	0.27	23.93	1.07	11.8	60.35
2003	47,985	0.83	60.7	1.48	1.5	0.18	23.8	1.1	11.5	60.44
2004	47,701	1.07	61.8	1.94	1.86	0.19	23.52	1.08	11.4	60.01
2005	47,832	1.08	61.9	2.19	1.41	0.18	23.55	1.15	11.6	59.92
2006	47,536	0.21	62	0.48	0.18	0.01	23.53	1.17	11.1	63.53
2007	47,422	0.47	62.2	1.31	0.03	<0.01	23.15	1.15	11.1	63.26
2008	43,231	1.4	62.4	3.94	0.01	<0.01	21.63	1.17	10.4	62.85
2009	43,928	2.27	61.9	6.31	<0.01	<0.01	20.89	1.11	9.79	61.9
2010	44,820	2.95	61.8	8.28	<0.01	<0.01	20.03	0.97	9.44	61.28
2011	49,296	2.97	62	8.41	<0.01	<0.01	19.28	0.72	9.19	62.4
2012	47,268	3.13	62.4	8.82	<0.01	<0.01	18.64	0.66	8.8	63.08
2013	48,568	3.24	62.6	9.06	<0.01	<0.01	18	0.6	8.82	63.52
2014	49,835	3.24	62.7	9.07	<0.01	<0.01	17.61	0.59	8.67	64.06
2015	50,132	3.38	-	9.28	<0.01	<0.01	17.81	0.59	8.31	64.01
2016	49,963	3.41	-	9.5	<0.01	<0.01	18.22	0.58	8.12	63.58
Summer										
1997	38,690	0.27	58.2	0.1	1.08	0.06	26.07	1.13	12.5	59.06
1998	39,072	0.65	58.1	0.59	1.91	0.23	26.26	1.14	11.5	58.37
1999	39,022	0.72	58.2	0.84	1.81	0.13	26.45	1.15	11.8	57.82
2000	38,259	0.66	57.7	0.84	1.62	0.24	27.35	1.15	11.8	57
2001	38,995	0.63	57.5	0.74	1.73	0.28	27.13	1.17	12.8	56.15
2002	40,794	0.71	57.7	0.93	1.73	0.34	26.9	1.1	12.1	56.9
2003	43,360	0.81	57.3	0.98	2.18	0.23	26.75	1.15	12.1	56.61

2004	43,036	0.97	58.1	1.52	2.19	0.2	26.85	1.15	11.2	56.89
2005	40,903	0.95	58.4	1.75	1.66	0.19	26.49	1.21	12	56.7
2006	44,907	0.16	58.2	0.44	0.03	<0.01	27.38	1.22	11.3	59.63
2007	43,968	0.46	58.2	1.29	0.01	<0.01	27.17	1.23	11.1	59.2
2008	39,141	1.41	59.2	3.97	<0.01	<0.01	24.7	1.2	10.5	59.63
2009	39,799	2.23	58.6	6.22	<0.01	<0.01	23.98	1.12	10.4	58.28
2010	39,405	2.93	58.9	8.24	<0.01	<0.01	23.06	1.04	9.69	57.97
2011	40,933	2.95	59.2	8.38	<0.01	<0.01	21.82	0.78	9.47	59.55
2012	42,009	3.1	59.5	8.78	<0.01	<0.01	21.31	0.69	9.54	59.68
2013	41,258	3.23	59.6	9.09	<0.01	<0.01	20.85	0.65	9.4	60.01
2014	41,882	3.25	59.8	9.21	<0.01	<0.01	20.56	0.64	9.29	60.3
2015	43,006	3.34	-	9.28	<0.01	<0.01	20.87	0.63	8.99	60.23
2016	41,979	3.41	-	9.54	<0.01	<0.01	21.07	0.63	8.38	60.38

Reformulated Gasoline:

Year	Volume	Oxygen	API	Ethanol	MTBE	TAME	Aromatics (non-benzene)	Benzene	Olefins	Saturates
	Million Gallons	Wt%	Gravity	Vol%	Vol%	Vol%	Vol%	Vol%	Vol%	Vol%
Winter										
1997	14,771	2.2	62.5	1.1	8.74	0.72	18.58	0.62	11.5	58.74
1998	14,922	2.22	62	1.16	8.94	0.71	19.15	0.65	10.9	58.49
1999	15,167	2.16	62	1.18	8.47	0.81	18.95	0.65	11.3	58.64
2000	15,951	2.12	62.4	1.22	8.21	0.74	18.35	0.65	11.8	59.03
2001	15,840	2.11	62.2	1.18	8.27	0.72	18.56	0.64	12.3	58.33
2002	16,435	2.09	62.2	1.31	8.01	0.59	18.76	0.64	11.1	59.59
2003	16,678	2.14	62.1	1.68	7.76	0.38	18.76	0.64	11	59.78
2004	17,209	2.38	62	2.68	7.03	0.33	18.47	0.63	11.1	59.76
2005	17,358	2.37	61.9	2.86	6.63	0.29	18.84	0.66	11.2	59.52
2006	17,388	3.11	61.3	6.96	3.47	0.01	18.84	0.66	10.8	59.26
2007	17,320	3.63	61.3	9.67	0.01	<0.01	18.26	0.64	11.1	60.32
2008	18,057	3.63	61.9	9.65	<0.01	<0.01	17.27	0.63	10.7	61.75
2009	17,896	3.63	61.7	9.65	<0.01	<0.01	17.06	0.64	10.5	62.15
2010	17,868	3.65	61.7	9.68	<0.01	<0.01	16.78	0.62	10.9	62.02
2011	17,380	3.66	62.4	9.67	<0.01	<0.01	16.02	0.58	10.8	62.93

2012	16,780	3.64	62.6	9.63	<0.01	<0.01	16.06	0.54	10.5	63.27
2013	16,741	3.67	63	9.66	<0.01	<0.01	15.79	0.51	10.4	63.64
2014	17,460	3.67	63.3	9.68	<0.01	<0.01	15.77	0.53	9.8	64.22
2015	17,946	3.68	-	9.7	<0.01	<0.01	15.87	0.53	9.55	64.35
2016	18,305	3.68	-	9.72	<0.01	<0.01	15.89	0.51	9.16	64.72
Summer										
1997	12,489	2.15	58	0.95	8.81	0.79	22.04	0.66	12.3	54.45
1998	12,751	2.13	57.9	1.02	8.91	0.79	22.03	0.67	11	55.58
1999	13,069	2.11	58.1	1.07	8.6	0.86	21.49	0.71	11.4	55.87
2000	13,067	2.24	58.9	1.14	9.04	0.95	18.71	0.59	10.6	58.97
2001	13,243	2.21	58.5	1.1	9.02	0.9	19.48	0.62	11.8	57.08
2002	13,853	2.25	58.5	1.3	8.95	0.76	19.81	0.59	10.8	57.79
2003	13,594	2.3	58.6	1.5	8.91	0.83	19.49	0.61	11	57.66
2004	14,220	2.55	58.2	3.04	7.42	0.42	19.51	0.59	11.4	57.62
2005	13,573	2.49	58.4	3.03	7.02	0.46	20.04	0.66	11.9	56.89
2006	13,347	3.52	57.6	9.5	0.16	0.01	19.51	0.59	11	59.23
2007	13,693	3.54	58.2	9.58	0.01	<0.01	18.93	0.57	11.6	59.31
2008	13,586	3.57	58.9	9.59	<0.01	<0.01	17.83	0.57	10.9	61.11
2009	13,780	3.55	58.3	9.59	<0.01	<0.01	18.14	0.56	11.3	60.41
2010	14,193	3.56	58.5	9.62	<0.01	<0.01	17.74	0.56	11.2	60.88
2011	13,522	3.56	58.6	9.61	<0.01	<0.01	17.56	0.54	12	60.29
2012	13,639	3.57	59.2	9.6	<0.01	<0.01	16.42	0.48	11.6	61.9
2013	13,123	3.57	59.4	9.59	<0.01	<0.01	16.51	0.49	11.1	62.31
2014	13,828	3.57	59.6	9.58	<0.01	<0.01	16.03	0.47	11.1	62.82
2015	14,303	3.57	-	9.61	<0.01	<0.01	16.62	0.48	10.9	62.39
2016	15,056	3.58	-	9.63	<0.01	<0.01	16.59	0.51	10.5	62.77

Notes on tables: These do not include California gasolines. Aromatics (non-benzene) calculated by removing benzene % from total aromatics.

Annex 2: API Gasoline Speciation Data Calculations

We used gasoline speciation data from the API ethanol blending study[7]. Of the total of 27 summer gasolines and 10 summertime blendstock for oxygenate blending (BOBs) which were collected and speciated for the analysis by API, we chose a low-RVP summer gasoline and we also picked a winter gasoline which contained an amount of aromatics which is typical of today's winter gasoline (today's gasoline contains about 20 volume percent aromatics). The list of gasoline constituents was sorted and the 33[8] most prevalent constituents were identified (two other constituents are reserved for ethanol and water). Since similar constituents were grouped together, a total of about 60 speciated hydrocarbons were represented by the list of 33 most prevalent constituents, representing a little more than 80 weight percent of the total volume of the speciated sample. To avoid the effects of volatility on the assessment of the effect of different gasoline constituents and water levels on RVP when ethanol is blended into gasoline, we adjusted the butane levels to closely match the RVPs of the several summertime gasolines that we evaluated. To avoid over-representing the very volatile constituents and overestimating the RVP of the speciated, representative gasoline, only the C8 and heavier hydrocarbons were increased to represent the approximately 20 weight percent of the unaccounted for gasoline blend (This is also reasonable because most of the gasoline hydrocarbons unaccounted for by the 35 substances modeled in the activity coefficient model are C8 and heavier).

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[7] Ethanol Blending Study and Spreadsheet provided by David Lax, American Petroleum Institute.

[8] 32 components are shown in Tables 8-10 since benzene is listed separately.