Chapter 10

A PROBABILISTIC RISK ASSESSMENT OF CLASS I HAZARDOUS WASTE INJECTION WELLS

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10.1 INTRODUCTION

The disposal of large volumes of industrial and municipal wastes has been a source of ongoing concern throughout the latter half of the twentieth century. Over the past 20 years, increasingly stringent waste-disposal regulations have improved environmental quality while limiting disposal options and raising costs. Because waste reduction techniques are equally subject to the law of diminishing returns, some waste will always result from human activities, and disposal issues will remain to be addressed. From a societal viewpoint, the ideal disposal method should be (virtually) infinite, cheap, permanent, and result in no human or ecological exposures in the foreseeable future. Most current regulated methods of disposal, for example, landfills or incineration, fail in one or more of these areas. Only deep-well injection appears to satisfy all four requirements; however, the environmental risks associated with Class IH disposal technology remains a source of controversy.

Approximately 150 underground injection wells exist in the United States that are categorized by the United States Environmental Protection Agency (EPA) as Class IH (U.S. Environmental Protection Agency, 1996) wells that inject hazardous liquid waste. The majority of Class IH wells are located in the Great Lakes Region and the Gulf States, due to the favorable geology in these regions. Over half of these wells are located in Texas and Louisiana, and almost 90% are in EPA Regions V and VI (U.S. Environmental Protection Agency, 1996). Based on figures from the EPA's TRI (U.S. Environmental Protection Agency, 1996), the volume of hazardous waste disposed of through Class IH deep-well injection is about 220 million pounds. This quantity is somewhat deceptive, since the practice of deep-well injection involves dilution of the waste with large amounts of water before it is pumped into the subsurface. Industries that practice deep-well injection are sometimes singled out as major sources of pollutant releases to the environment. Since the intent of deep-well injection is the permanent *isolation* of waste *from* the biosphere, it is unclear if the use of deep-well injection can be properly considered a *release to* the environment. While problems resulting from deep-well injection have occurred, these incidents took place in the past, and the conditions that caused them do not occur under current regulations and practices.

In 1980, the EPA promulgated regulations governing all injection wells, including those injecting hazardous waste (53 FR 28131). In 1988, EPA passed additional regulations requiring operators of Class IH wells to demonstrate that no migration of the waste constituents will occur from the injection zone while the waste remains hazardous (or for 10,000 years) (40 CFR Parts 146 and 148). Waste isolation is accomplished by a combination of:

- The application of strict siting criteria.
- The presence of multiple redundant engineered and geological barriers.
- Practices to ensure chemical compatibility of waste with geology.
- Operating restrictions and preventive maintenance during active injection operations.
- Continual monitoring and testing of performance and confinement integrity.
- The presence of alarms and a full-time operator.

These factors combine to assure that waste will be prevented from entering the accessible environment, i.e., that portion of the environment where human or ecological exposure can occur. In the absence of such exposure, no risk to human health or welfare exists.

Studies published by both industry and the EPA in the past 10 years have concluded that the current practice of deep-well injection is both safe and effective, and poses an acceptably low risk to the environment (CH2M Hill, 1986a; Clark, 1994; Department of Energy and Natural Resources et al., 1989; Underground Injection Practices Council, 1987; U.S. Environmental Protection Agency, 1985, 1989, 1991; Ward et al., 1987). Nonetheless, various advocacy groups have challenged the effectiveness of deep-well-injection regulations, and have opposed the practice on principle (Gordon and Bloom, 1985; MacLean and Puchalsky, 1994; Sierra Club Legal Defense Fund, 1989). Studies purporting to examine the risks from deep-well injection take as their starting point the assumption that release of waste from confinement to a drinking water aquifer has already occurred and then model the transport time to a receptor well and the dose received by that receptor (The Cadmus Group, Inc., 1995). None of these studies to date has assessed the probability of the release even occurring in the first place. Since the primary risk associated with deep-well injection is that isolation from the accessible environment might fail, this probability must be examined before drawing any conclusions regarding health or environmental risks from such a release.

The purpose of this paper is to examine the risk from such a failure of isolation, and to provide an objective and quantitative analysis of the risk of waste isolation loss from Class IH underground injection wells that will allow meaningful identification and comparison of waste isolation subsystems as contributors to that risk. Areas of uncertainty will be identified and quantified as to their possible contribution and importance to the risk estimates for the purposes of collecting additional data, identifying new sources of data, or stimulating new research to reduce these uncertainties. In doing so, we hope to provide all stakeholders with the type of rigorous scientific support needed to make appropriate decisions regarding deep-well injection.

10.2 BACKGROUND

A review of available studies on Class I injection well failures over the past 20 years was conducted. These studies originated from a variety of sources, including industry studies, peer-reviewed studies, trade association reports, as well as reports from advocacy groups. Case studies and accident reports involving injection wells were reviewed as well. The relevant regulations were also carefully reviewed to determine the ways that regulatory requirements and restrictions affect siting, design, construction, and operations. Numerous discussions and interviews were held with injection well operators and regulators. Based on this information, the critical factors to maintaining waste isolation were identified.

An important concept that appears throughout injection well risk studies and regulations is that of USDW. Releases from injection wells into the accessible environment (i.e., that portion of the environment where human or ecological exposures can occur) may occur either at the ground surface, or at subsurface groundwater zones that have potential human use. These subsurface groundwater zones are typically called USDWs in studies and regulations. While surface releases are readily observed and remedied, and as such do not result in chronic exposures and have not been included in risk assessments, potential releases to USDWs are the primary focus of risk assessments and regulations. Accordingly, this assessment assumes the relevant release point to be the lowermost USDW (i.e., closest to the injection zone).

In general, previous studies fall into four categories. The first category is case studies of injection-well failures that have resulted in releases (CH2M Hill, 1986b; Clark, 1987; Engineering Enterprises, Inc. et al., 1986; Ken E. Davis Associates, 1986; Paque, 1986; Underground Resource Management, Inc., 1984). There are relatively few cases of this sort and none involving a release from a Class I well to a USDW since the EPA regulations took effect in 1980 (U.S. Environmental Protection Agency, 1985, 1991). These historical incidents are confined without exception to issues of well siting, design, and operation practices that are no longer allowed under today's regulations, nor do they exist in today's population of Class I wells (Clark, 1994; Engineering Enterprises Inc. et al., 1986; Ken E. Davis Associates, 1986; Paque, 1986; Underground Resource Management, Inc., 1984; U.S. Environmental Protection Agency, 1991).

The second category is geologic fate and transport modeling studies (Buss et al., 1984; Davis, 1987; Don L. Warner, Inc. and Engineering Enterprises, Inc., 1984; Goolsby, 1972; Meritt, 1984; Miller et al., 1986; Morganwalp and Smith, 1988; Scrivner et al., 1986; U.S. Environmental Protection Agency, 1990a, 1990b; Ward et al., 1987). These studies assume a release from an injection well, and model the fate and transport of contaminants as they migrate through the typical geologic formations associated with injection wells. These include modeling efforts performed for the "no-migration petition" required for an operating permit. In general, such studies demonstrate that the proper selection of the geologic formation creates an effective means to achieve waste isolation. While such studies can provide useful information on geologic factors important for maintaining waste isolation, and on the potential for failure of geologic barriers, they assume that a release has already occurred and do not account for waste isolation provided by engineered barriers of the well system. These studies can help with understanding mechanisms and the likelihood of failure of geologic formation as one component of the loss of waste isolation, and can help in developing estimates of release volumes and concentrations to USDWs.

The third category is properly characterized as exposure studies (The Cadmus Group, Inc., 1995). One study of this type was found. In this study, it was assumed that a release occurred from the injection well to the USDW. The transport of this release into the USDW aquifer was modeled to a point of withdrawal for potable use. As with other modeling studies, a release was assumed without providing any information on how the release occurred and the probability of that release mechanism. Additionally, such studies do not take into account the effect of the containment or attenuation factors posed by geologic features (e.g., layers of low-permeability rock) between the point of release and the USDW.

The final category is regulatory reviews and comparative risk studies. A 1989 EPA comparative risk evaluation of waste management alternatives by experts in the field concluded that deep-well injection posed among the lowest environmental risks on a relative scale

(U.S. Environmental Protection Agency, 1989). A 1991 EPA analysis of their restrictions on Class IH wells concluded that since 1980, Class IH wells are safer than virtually all other waste disposal practices (U.S. Environmental Protection Agency, 1991). EPA studied over 500 Class I wells in operation from 1988 to 1991 and found no failures known to have affected a USDW. In response to a 1992 House of Representatives subcommittee inquiry, EPA (U.S. Environmental Protection Agency, 1993) provided state-by-state summaries of reported Class I well failure incidents between 1988 and 1992. This was defined as a breakdown or operational failure of components of the well system, whether waste isolation loss occurred or not. Although component failures were reported during the survey period, no waste isolation failure occurred, and no waste from a Class I injection well reached a USDW. While these studies indicate the waste isolation effectiveness of current injection practices, they do not quantitatively address future risk.

In summary, no studies were identified that provide full quantitative characterization of the risk of Class I hazardous waste injection wells. Some describe release incidents for well systems that cannot and do not exist under today's regulations. Others characterize only a portion of the risk, for example, estimating exposures that might occur after presuming a release (often by mechanisms that have never occurred). Others demonstrate that releases have not occurred under current practices, but do not characterize the likelihood that releases might occur in the future. To properly assess the environmental risks posed by Class I injection wells, it is critical that the probability of loss of waste isolation be quantitatively assessed. Waste volumes and concentrations corresponding to realistic release scenarios should be included in the assessment.

10.3 METHODOLOGY

To quantitatively evaluate environmental risks posed by Class IH well injection, it was necessary to develop a detailed characterization of how the siting, construction, design, operation, testing, and maintenance of a Class IH well system function as a whole to ensure waste isolation (Buttram, 1986; CH2M Hill, 1986a; Underground Injection Practices Council, 1986; SCS Engineers, 1985; Warner and Lehr, 1977). The critical elements of this system that are important in maintaining waste isolation are singled out for special attention. Inherent in this approach is a systematic identification and depiction of events and conditions that could result in loss of waste isolation. This information was gathered from historical records on well failure events, and obtained from interviews with injection well construction, maintenance, and testing practitioner; operators of injection wells; and the agencies that regulate them. From this information, a comprehensive set of scenarios depicting the ways in which a typical Class IH injection well system could fail to isolate waste was developed. The probability of waste isolation loss in each of these scenarios was then quantified. Uncertainties in the analysis were given explicit quantitative treatment using Monte Carlo analysis.

More specifically, the techniques of probabilistic risk assessment (PRA) were employed. PRA is a generally accepted approach for analyzing risks that arise through failure of engineered systems. In this case, PRA was used to identify sequences of events by which waste isolation could fail and result in waste reaching the lowermost USDW, and to characterize the probabilities of these event sequences. The results quantitatively and probabilistically demonstrate the degree of certainty that waste injected in this manner will effectively remain isolated and pose no future risk. The outcome of interest to this study was that the loss of waste isolation by release to the lowermost USDW could be due to any cause. Factors considered included:

- Errors in site selection or characterization, such as inappropriate or incompatible geology, unidentified abandoned wells, undetected geologic faults, or incorrect characterization of waste migration potential.
- Geologic or engineered system failures, such as seismic fracturing of confining zones, tubing, or casing breaches, annulus fluid pressure loss, or alarm failures.
- Operator errors, such as failure to respond to alarms, failure to detect leaks during testing, overpressurizing, or injecting incompatible waste.
- Other possible human errors, such as inadvertent extraction of waste in the future.

The following steps were taken, and detailed discussion of each follows:

1. The Class IH well system, individual components, and conditions on which the PRA is based were defined.
2. FMEA was performed with the assistance of injection well experts.
3. Based on FMEA results, event and fault trees were developed, depicting the sequence of events that must occur for waste isolation to be lost.
4. Based on historical or expert information, probability distributions characterizing the uncertainty in the frequency of occurrence of the various failures and other events were developed.
5. Boolean logic and Monte Carlo analysis were used to combine the frequencies of independent and dependent events as depicted in the event and fault trees to estimate the overall probability of waste isolation loss for a Class IH well.

10.4 CLASS IH INJECTION WELL SYSTEM DEFINITION

In order to quantitatively assess the risk of loss of waste isolation from Class IH injection wells, the injection well system must be defined at a high enough level of detail so that specific event sequences can be identified and their frequencies quantified. At the same time, the system definition must not be so unique that its methodologies and conclusions cannot be generalized to the population of Class IH wells as a whole. The Class IH well system definition used for this study was based on the minimal design and operation features allowed under current regulations; this ensures the broadest applicability of this study's results and conclusions. The regulatory system is sufficiently effective to eliminate the possibility of any Class IH injection wells that do not at least meet the system definition. This conclusion was verified by discussions with state and EPA officials, a review of the current EPA injection well database (U.S. Environmental Protection Agency, 1996), and a random survey of Class I injection well operators of about 20% of the currently operating Class IH wells (Woodward Clyde Consultants, 1995). It was nonetheless appropriate to evaluate the possible failure of certain elements of the regulatory process that influence the effectiveness of waste isolation; this was done (e.g., the possibility that an unplugged well in the area is unaccounted for in the site review was included in the study).

The design and operation features of the system analyzed are listed in Table 10.1, and a diagram of the system is shown in Figure 10.1. As a standard Class IH injection well, the system is assumed to comply with the requirements of the Code of Federal Regulations, Chapter 40, Parts 146 and 148, and Part 267 (Subpart G). The salient features of these requirements with respect to waste isolation are listed in Table 10.1. It is assumed that the

Table 10.1. Class IH well system definitions—design and operating features

Waste isolation element	Design or operating feature
Applicable regulation	Complies with 40 CFR 146 Subpart G
Site selection and characterization	Area of Review: 2-mile radius. "No-migration petition" for injection of restricted wastes.
Geologic barriers	Two confining layers between the injection zone and the lowermost USDW
Engineered barriers	Surface casing set below lowermost USDW. Casing completed with continuous cement. Liquid-based annulus pressure barrier
Testing, monitoring, and inspection	Equipped with auto-alarm and a full-time operator. Annual Radioactive Tracer survey or OA log for fluid movement temperature, and noise logs once every 5 years

well operator has prepared a no-migration petition, which is required to receive a permit to inject restricted wastes. The no-migration petition results in a marked increase in site and system scrutiny by both the industry and the regulators. The operator must demonstrate through modeling that no migration of the waste will occur from the injection zone while the waste remains hazardous (or for 10,000 years). Petitions such as the no-migration petition extensively document the local geology and faults, the well design, the operation and maintenance procedures, comprehensive local well surveys, and fate and transport through mathematical modeling. In the process of characterizing the proposed injection site, an area of review (AOR), extending for a two-mile radius around the site, must be investigated. The impact of these extensive analyses and investigations need to be considered in assessing the probability of release.

The geologic features of the system analyzed are depicted in Figure 10.1. The *injection zone* is the permeable subsurface rock that receives the waste. Class I injection well depths range from 1700 to 9500 ft nationwide (U.S. Environmental Protection Agency, 1996). Typically, the USDW and injection zone are separated by several thousand feet (U.S. Environmental Protection Agency, 1996). The injection zone is required to be separated from the USDW by at least two confining zones consisting of dense rock or other geologic formations impermeable to fluid migration. For this assessment, it was assumed that only two confining zones exist. In actual practice, Class I injection wells have more than two confining layers (U.S. Environmental Protection Agency, 1996), which are separated by nonpotable water-bearing zones called "buffer zones." Studies have shown that if waste fluid were to migrate through a confining zone, there would be significant dilution in each successive buffer (Don L. Warner, Inc. and Engineering Enterprises, Inc., 1984; U.S. Environmental Protection Agency, 1990). This phenomenon has not been accounted for in exposure assessments to date (The Cadmus Group, Inc., 1995), which generally assume that the waste inventory is released directly to a USDW.

Injection wells are constructed by extending concentric pipes or *casings* down the drilled well boring. Corrosion-resistant materials such as steel alloy or fiberglass are used in the

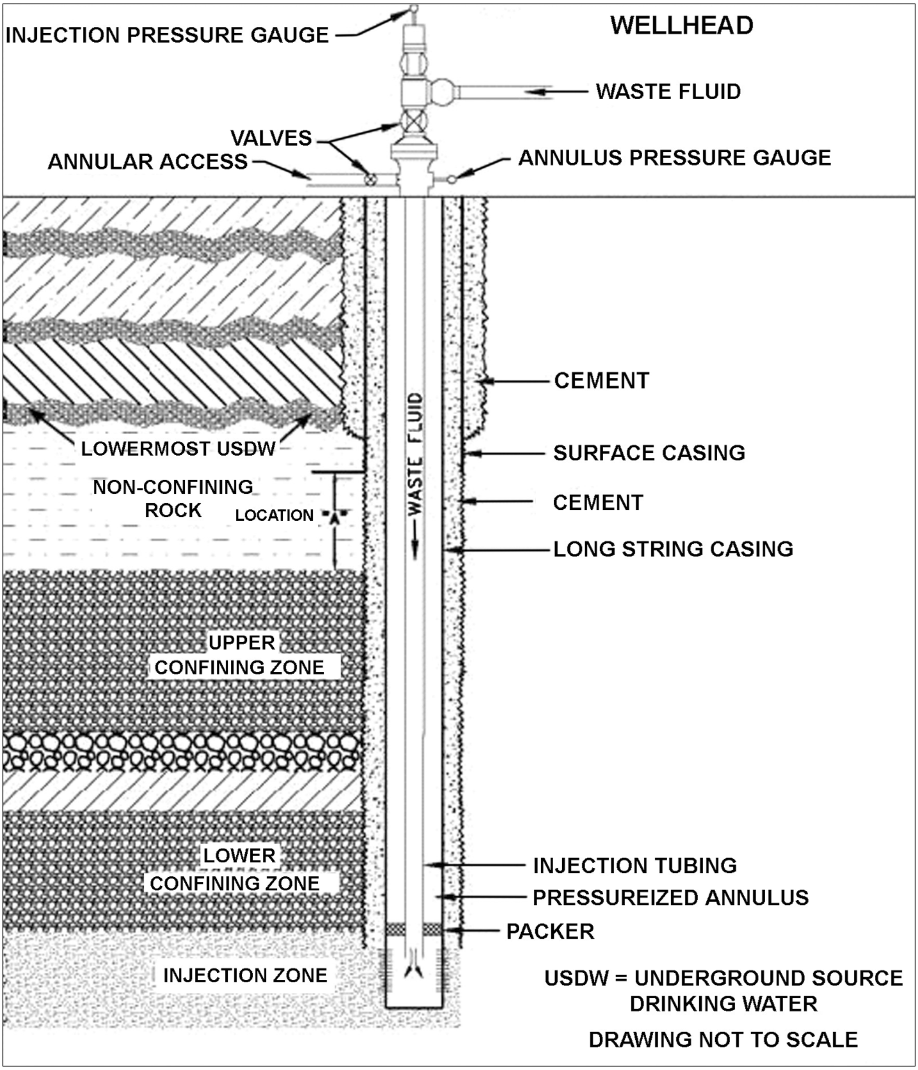

Fig. 10.1. Simplified Class I injection well system assumed for PRA.

casings. The upper and outermost casing (Fig. 10.1) is called the *surface casing*, and is required by regulation (Table 10.1) to extend below the base of the lowermost USDW. As shown in Figure 10.1, the surface casing might not extend into the uppermost confining zone. This could result in a section of the well without surface casing to pass through an area of non-confining rock, below the lowermost USDW, but above the confining zones (see *Location A* in Fig. 10.1). This area is important in the PRA, because it is the location with the least number of barriers to loss of waste isolation.

Within the surface casing is the *long string casing*, which extends to the injection zone. Chemically resistant cement or epoxy resin is used to fill the borehole space outside the surface casing, between the surface and long string casings; and the borehole space outside the long string casing, from top to bottom. These casings were assumed to be completed with continuous cement (Table 10.1); this effectively binds the casings together and seals the well boring along its entire length, creating a single unit. Nonetheless, in this conservative assessment, the cement was considered a barrier for vertical but not horizontal fluid migration.

A smaller steel or fiberglass pipe, the *injection tube*, extends the length of the casings through a lower seal (the *packer*) into the injection zone. Waste pumped from above flows into and is forced out of the portion of the borehole that extends into the injection zone. This is known as the *injection interval*, and may be uncased or fitted with a perforated section to prevent loose material from entering and potentially clogging the borehole or injection tube.

The space between the long string casing and the injection tube (*the annulus*) is sealed at the surface by the wellhead and at the base by the *packer*, and filled with a noncorrosive fluid under positive pressure in excess of the injection tube pressure. In Class IH wells, the annulus fluid is required to function as an additional pressure barrier to prevent waste fluid from leaking through the injection tube or the packer. Measurement of the fluid pressure and volume within the annulus is used to monitor the mechanical integrity of the injection tube, long string casing, and packer.

An operating Class IH injection well system incorporates the redundancy of safety systems that typically characterize safe engineering design. The long string casing is continuously cemented from top to bottom. Along with the annulus fluid pressure, the casing is a barrier to an injection tube or packer leak, and the cement provides a barrier to vertical migration of any fluid that would escape along the outside of the casing or the borehole. The surface casing presents another barrier to waste migration in the portion of the well passing through USDWs. Finally, the annulus is sealed at both ends and is pressurized. Because the pressure in the annulus is higher than the pressure used to inject the waste (positive pressure), any leaks in the injection tube would result in annulus fluid being forced into the tube rather than waste fluid escaping into the annulus. The fluid pressure is required to be continuously monitored both by automated alarm systems and manually by a full-time operator for loss of pressure or volume. Such loss could indicate that the system integrity is compromised (e.g., pump failure, packer failure, casing failure). Most Class IH systems include automatic shutdown of the injection pumps upon alarm, although it was conservatively assumed that the system assessed did not have an auto-shutdown feature. Of course, the injection pumps shut down upon loss-of-power events.

Class IH wells are monitored annually for a number of factors related to waste isolation, including injection zone pressure buildup, water quality monitoring in lower USDW in some cases, and required mechanical integrity testing to detect fluid movement outside the long string casing. Such testing includes annual radioactive tracer or oxygen activation logging, as well as temperature and noise logging at least once every 5 years. Casing inspection logs are required whenever the injection tube is removed. When migration or flaws are detected, they are repaired.

In summary, the system assessed was a Class I hazardous waste injection well that minimally complies with 40 CFR 146 Subpart G requirements. The system components included in the PRA included geologic, engineered, and human elements. Finally, the system was assumed to be operating, with an operating lifetime of 30 years. Post-operating risks analyzed included the possibility of inadvertent human extraction of waste and migration through breached geologic confining zones.

10.5 FAILURE MODES AND EFFECTS ANALYSIS

FMEA was performed on the Class IH injection well system defined above. This is a systematic technique for identifying all means by which the injection well components could fail, and what the effect could be with respect to waste isolation. Each component and activity identified as important was evaluated by:

- Identifying all possible failure modes of the component (e.g., injection tube leaks, injection tube crushes, injection tube plugs, etc.).
- Identifying possible reasons for these failure modes (e.g., corrosion, improper installation, etc.).
- Assessing possible consequences of the failure mode (e.g., loss of annulus pressure, fracturing of injection zone, etc.).
- Identifying system features that serve to prevent the failure or mitigate its consequences (e.g., the annulus fluid is under positive pressure).

The FMEA process is a brainstorming activity that does not exclude events based on the probability of their occurrence. All plausible events are considered even if they are considered to be of very low probability. The results of the FMEA are qualitative in nature and are not in themselves suitable for quantifying risk. Because the FMEA identifies all potential failure modes for the system, failure mechanisms of the components, and the safety systems designed to prevent or mitigate failures, it creates a level of understanding that can be used to develop the probabilistic framework to quantify risk (i.e., the event and fault trees).

The FMEA process in this assessment was one through a series of workshops with deep-well injection operators and expert consultants. In addition, FMEA results were presented at a number of Ground Water Protection Council national meetings, and refined through input obtained from injection well operators, maintenance and testing professionals, and state and EPA regulatory staff who attended the meetings.

10.6 EVENT AND FAULT TREE DEVELOPMENT

Based on the understanding gained from the FMEA, event trees were developed that identify potential sequences of events that could result in a release to the lowermost USDW. Seven possible initiating events were identified that characterize the overall risk of waste isolation loss for the Class IH injection well system defined. The seven initiating events identified were:

1. Packer leak
2. Major packer failure
3. Injection tube leak
4. Major injection tube failure
5. Cement microannulus leak
6. Confining zone(s) breach
7. Inadvertent injection zone extraction

Once initiated, the likelihood of waste isolation loss depends on the subsequent failure of additional components, barriers, and backup systems within a relevant time domain. The event tree is a diagram that depicts the sequence of events and component failures that must follow for a release to the lowermost USDW to occur. A pathway can be traced through the event tree along its branches, depicting different combinations of failures and successes of system components and operational events that function together to prevent or result in waste isolation loss.

Fault trees were developed for three events of sufficient complexity, involving multiple events themselves. These three events were: loss of the annulus pressure barrier, lower geologic confining zone breach, and upper geologic confining zone breach.

The event and fault trees for each initiating event sequence are discussed in more detail below, with estimated frequencies of occurrence for events in the trees described first.

10.7 EVENT-FREQUENCY-DISTRIBUTION DEVELOPMENT

Perhaps the most problematic part of this PRA was estimating frequencies of occurrence for events in the trees. For many of these events, occurrence was so rare and data were so sparse that a confident point estimate for the frequency of occurrence could not be established. Consequently, uncertainty about occurrence frequencies was given explicit quantitative treatment in the assessment. Probability distributions of event occurrence frequencies were developed, either based on available occurrence data or expert judgment. These distributions are shown in Table 10.2, where the event names correspond to event names appearing on the event and fault trees in Figures 10.2–10.11. Simultaneous occurrence of the events in a sequence is required for a release to occur. The period of time during which simultaneous occurrence could feasibly happen before detection and remedy would occur was assumed to be one day. Thus, the frequencies shown in Table 10.2 are based on a daily time frame, unless they are on-demand probabilities of a failed state or response once a sequence is in progress (e.g., the probability that an alarm fails or the probability that a discontinuity is present in the confining zone).

10.8 QUANTITATIVE ANALYSIS OF EVENT TREES

In PRA, event frequencies are combined according to the logic of the event and fault trees using Boolean algebra. The result is the estimated frequency (or probability) of a release to the lowermost USDW over the lifetime of the Class I hazardous waste injection well. Since uncertain event frequencies in this assessment were characterized by probability distributions, these distributions were propagated through the Boolean algebra calculations using Monte Carlo analysis. The result is expressed as a distribution of the probability that waste isolation will be lost during the lifetime of the injection well. This approach enables one to draw conclusions as to the certainty of the waste isolation loss risk estimates, and to conduct sensitivity analyses to identify which individual events contribute the most uncertainty to the risk estimates. To facilitate such analyses, both fault and event tree probabilities were placed into Microsoft Excel™ spreadsheets while the random sampling and generation of stochastic results were performed using Crystal Ball™. Latin Hypercube Sampling (LHS) was used to generate input values for all distributions. The analysis was performed with 5000 iterations to provide the best possible estimate of the percentiles. For operator errors likely to involve the same operator or similarly trained operators, the frequency distributions were correlated. A parametric sensitivity analysis was also performed based on percent contribution of uncertain event frequencies to the overall variance in the loss of waste isolation probability distribution.

10.9 PROBABILISTIC RISK ASSESSMENT (PRA) RESULTS

Using the event and fault trees, the risk of waste isolation loss and release to the USDW over the 30-year life of a Class IH waste injection well was characterized quantitatively. Most of the

Table 10.2. Event probability distributions for a Class I hazardous waste injection well

Event name	Description	Probability distribution type	Lower bound	Median	Upper bound
ALARM	Automatic alarm fails	Uniform	5E–05	3E–04	5E–04
ANNPRESSLO	Annulus pressure drops below injection pressure	From fault tree	9E–14	7E–12	8E–11
CAPLOSS	Loss of injection zone capacity results in overpressurization	Uniform	1E–05	1E–04	1E–03
CHECKPA	Annulus check valve fails to open	Triangular	1E–04	3E–04	1E–03
CONFINEBRCHL	Transmissive breach occurs through lower confining zone	From fault tree	6E–04	3E–03	1E–02
CONFINEBRCHU	Transmissive breach occurs through upper confining zone	From fault tree	6E–04	3E–03	1E–02
CONTROLPA	Annulus pressure control system fails, resulting in underpressurization	Uniform	1E–06	1E–05	1E–04
CONTROLPI	Injection pressure control system fails, resulting in overpressurization	Uniform	1E–06	1E–05	1E–04
DETECTWELL	Failure to identify abandoned well in AOR	Uniform	1E–03	5E–03	1E–02
DISCONT	Presence of unidentified transmissive discontinuity	Uniform	1E–04	1E–03	1E–02
EXTRACT	Extraction of injection zone groundwater	Uniform	1E–05	1E–04	1E–03
FLUIDTEST	Testing fails to detect injection fluid migration along outside of long string casing	Uniform	5E–04	3E–03	5E–03
INCOMPWASTE	Waste injected chemically incompatible with geology or previously injected waste	Uniform	1E–05	5E–05	1E–04
ITUBFAIL	Sudden/major failure and breach of injection tube	Poisson	3E–07	6E–07	8E–07
ITUBLEAK	Injection tube leak	Poisson	3E–05	6E–05	8E–05
LBUOYANCY	Injected fluid is sufficiently buoyant to penetrate lower confining zone breach	Single value	1E+00	1E+00	1E+00
LOCATION A	Long string casing leak located between surface	Uniform	1E–02	3E–02	5E–02

Table 10.2. *(continued)*

Event name	Description	Probability distribution type	Lower bound	Median	Upper bound
LOCATION B	Long string casing leak located above base of surface casing	Uniform	1E–02	5E–02	1E–01
LOCATION C	Long string casing leak is located below confining zone(s)	Uniform	9E–01	9E–01	1E+00
LSCASEFAIL	Sudden/major failure and breach of long string casing	Poisson	2E–07	3E–07	5E–07
LSCEMLEAK	Long string casing cement microannulus allows fluid movement along casing	Poisson	2E–06	6E–06	1E–05
LSTRINGLEAK	Long string casing leak	Poisson	2E–05	3E–05	5E–05
MIGRATION A	Waste migrates up microannulus to Location A between surface casing and upper confining zone	Uniform	1E–04	1E–03	1E–02
NORECOGNIZE	Failure to recognize groundwater extraction located within injection waste zone	Uniform	1E–03	5E–03	1E–02
OPERINJ	Operator fails to recognize changes in confining zone capacity	Uniform*	5E–05	3E–05	5E–04
OPERRDET	Operator fails to detect/respond to unacceptable pressure differential	Uniform*	5E–05	3E–05	5E–04
OPERRFRAC	Operator error results in induced transmissive fracture through the lower confining zone	Uniform*	5E–05	3E–04	5E–04
OPERRPA	Operator error causes annulus pressure below injection pressure	Uniform*	5E–05	3E–04	5E–04

OPERRPI	Operator error causes injection pressure above annulus pressure	Uniform*	5E–05	3E–04	5E–04
OUTAOR	Injection waste has migrated outside of Area of Review to unconfined zone	Uniform	1E–05	5E–05	1E–04
PACKFAIL	Sudden/major failure and breach of packer	Poisson	2E–07	4E–07	6E–07
PACKLEAK	Packer leak	Poisson	2E–05	4E–05	6E–05
PERMEA	Confining zone has unexpected transmissive permeability	Uniform	1E–05	1E–04	1E–03
PLUGFAIL	Identified abandoned well plug fails	Poisson	2E–04	8E–04	2E–03
PUMPPA	Annulus pump fails	Triangular	5E–05	5E–04	5E–03
RELDETECT	Groundwater monitoring fails to detect waste release outside injection zone	Single value	5E–01	5E–01	5E–01
SEISMFAULT	Seismic event induces a transmissive fault or fracture	Uniform	1E–05	5E–05	1E–04
SURFCASELEAK	Surface casing leak	Poisson	2E–06	3E–06	5E–06
TRANSLCZ	Unidentified abandoned well transmissive from injection zone through lower confining zone	Single value	1E–01	1E–01	1E–01
TRANSUSDW	Unidentified abandoned well transmissive through upper confining zone to USDW	Single value	1E–01	1E–01	1E–01
UBUOYANCY	Injected fluid is sufficiently buoyant to penetrate upper confining zone breach	Same as OPERRDET	1E–05	5E–05	1E–04
WASTEPRESENT	Injected waste has not transformed into nonwaste	Uniform	1E–02	1E–01	1E+00

Note: Frequencies are per day or per demand.

*Operator error event probability distributions are correlated ($r = 0.5$) to account for same operator or similar training.

trees represent the daily probability of the event sequence, and their results were converted into 30-year probabilities for presentation (see Table 10.3). Events that are independent of time (i.e., inadvertent injection zone extraction) are presented as event probabilities. The cumulative percentile results of the analysis for each event sequence are presented in Table 10.3. Values shown in Table 10.3 are probabilities of the loss of waste isolation (i.e., release to the lowermost USDW) over the lifetime of the well. The cumulative percentile is the likelihood of being less than or equal to (i.e., likelihood of not exceeding) the corresponding loss of isolation risk.

10.9.1 Packer Leak

The initiating event in this sequence is the development of a leak in the packer at the base of the injection tube and pressurized annulus (see Fig. 10.2). If the packer leaks during injection, containment is maintained as long as the annulus pressure is greater than the injection pressure. If the annulus pressure drops, containment will still be maintained by the long string casing. A leak in the long string casing might occur, but its location will be critical since this determines what additional failures must occur to lose containment. A long string casing leak in the area between the bottom of the surface casing and the upper confining zone (Location A) was assumed to result in a release to the lowermost USDW, even though current regulations require the surface casing to be set below the base of the lowermost USDW, into a confining bed. In addition, there actually may be significant geologic interaction between this point and the USDW. If the long string casing leak is located above the base of the surface casing, a release to the USDW requires either a leak in the surface casing or a crack (microannulus) in the long string cement casing that opens to Location A. A leak below the confining layer(s) requires a breach of the geologic barrier(s) or a microannulus that opens to Location A.

Two component failures in the event tree are described by fault trees: the first quantifies the probability that the annulus pressure is less than the injection pressure, while the second addresses the probability that the confining zone is breached. These fault trees are presented in Figures 10.3 and 10.4, respectively, while the event probabilities associated with these fault trees are shown in Table 10.2.

The PRA results of the packer leak scenario indicate that the probability of waste isolation loss over the life of the well from this initiating event is on the order of 10^{-17}–10^{-18} (see Table 10.3). The annulus pressure is the primary barrier to loss of containment, and the probability of pressure loss is extremely low, since it would require simultaneous alarm and full-time operator failures. In fact, a difference in pressure between the annulus and injection fluids does occur, but the high reliability of the redundant auto-alarm and full-time operator keeps the probability of this extremely low, resulting in a pressure barrier loss during injection. Additionally, the location of a long string casing leak is a critical factor in waste isolation loss, as it determines the presence or absence of additional barriers.

10.9.2 Major Packer Failure

This event is distinguished from the packer leak event in that it involves a complete and sudden loss of the packer and the subsequent rapid loss of annulus pressure (see Fig. 10.5). Without the annulus pressure barrier, the containment now depends on the integrity of the long string casing and associated components. The sequence of component failure leading to waste isolation loss thereafter is similar to the packer leak tree, except there is no annulus pressure barrier.

Table 10.3. Cumulative percent results for each loss of waste isolation event in a Class I hazardous waste injection well

Cumulative percentile[*]	Packer leak	Sudden packer failure	Injection tube leak	Sudden injection tube failure	Cement microannulus	Confining zones fail	Inadvertent extraction
0	2.05E–20	7.73E–10	3.31E–20	1.15E–09	0.00E+00	5.05E–12	2.35E–10
10	5.35E–19	2.05E–09	8.46E–19	3.22E–09	1.78E–08	6.37E–11	3.55E–09
25	1.18E–18	2.82E–09	1.85E–18	4.45E–09	4.33E–08	1.20E–10	1.22E–08
50	2.67E–18	4.08E–09	4.19E–18	6.35E–09	1.35E–07	2.38E–10	4.79E–08
75	5.76E–18	5.53E–09	8.98E–18	8.54E–09	4.50E–07	4.80E–10	1.94E–07
90	1.11E–17	7.00E–09	1.77E–17	1.06E–08	1.04E–06	8.98E–10	6.41E–07
100	9.12E–17	1.32E–08	1.09E–16	2.08E–08	4.57E–06	6.39E–09	8.64E–06

[*] Cumulative percentile is the likelihood of being less than or equal to (i.e., not exceeding) the corresponding loss of isolation risk.

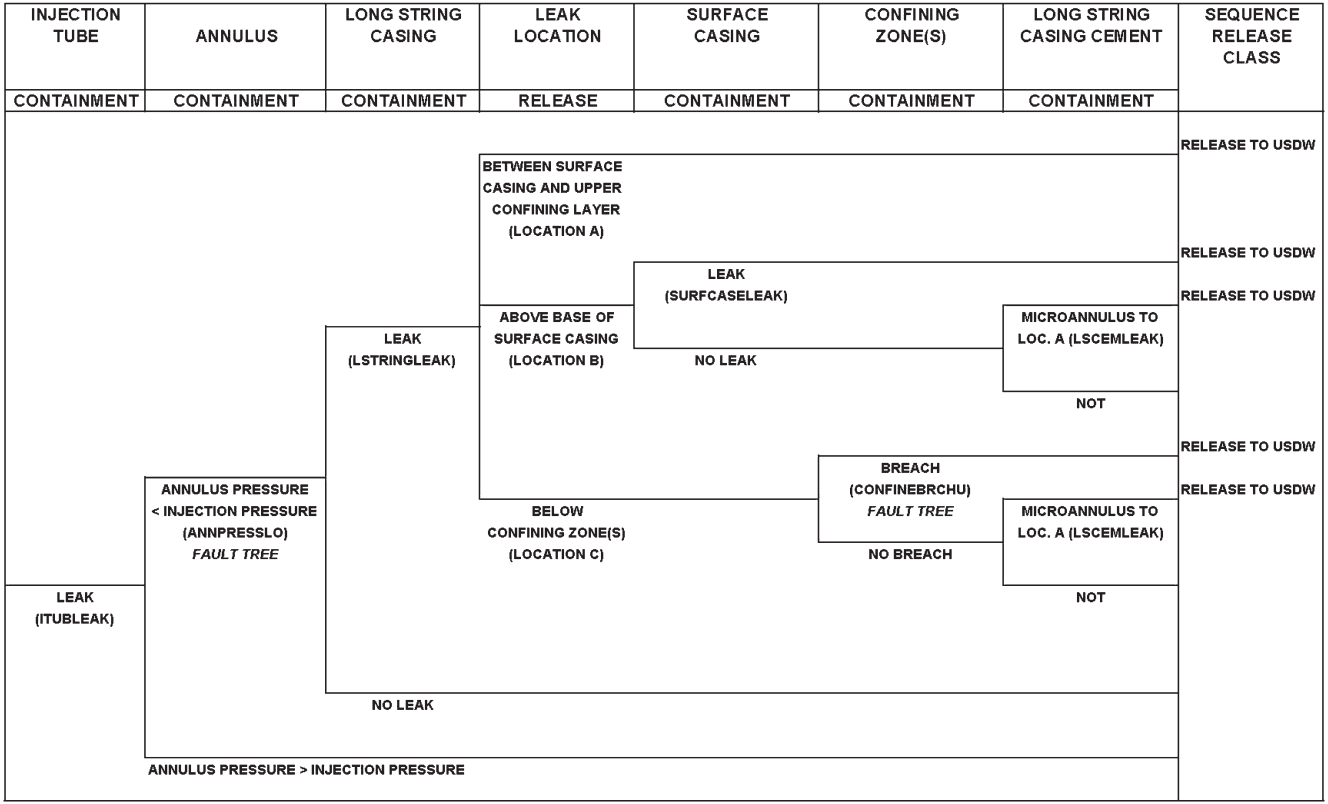

Fig. 10.2. Event tree for packer leak in a Class I hazardous waste injection well.

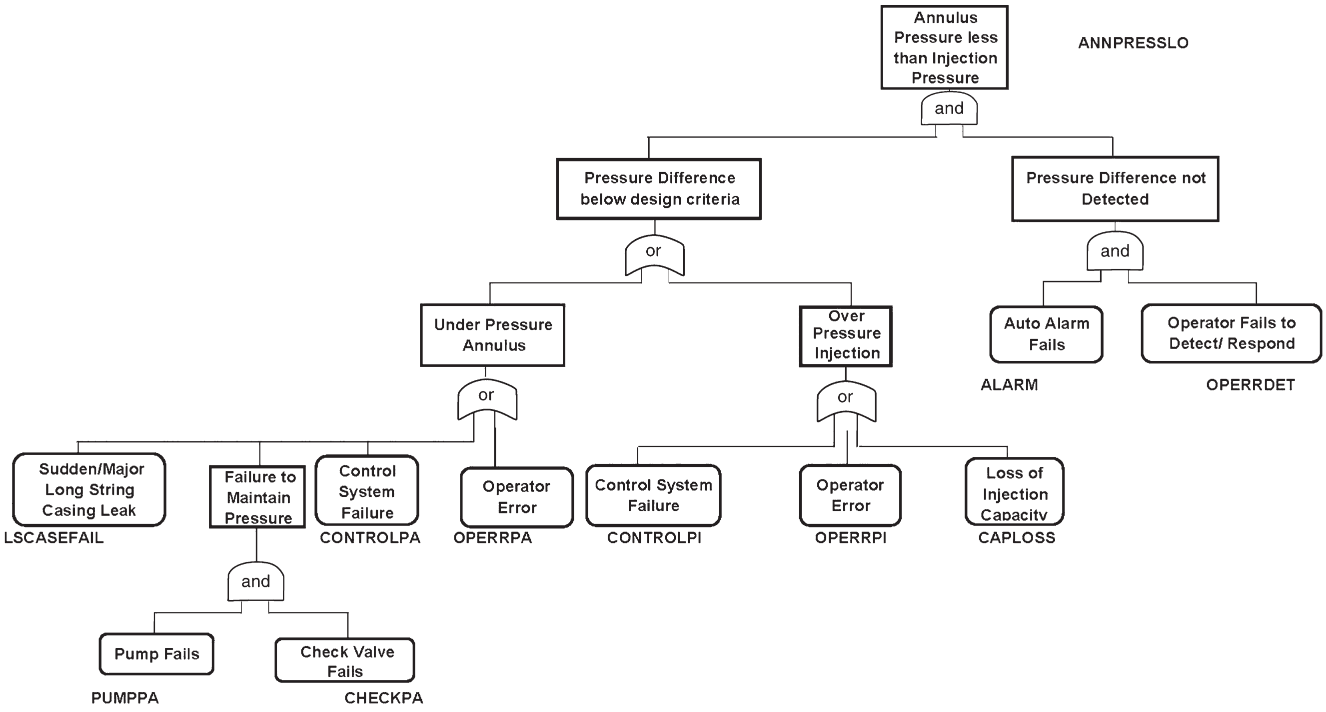

Fig. 10.3. Fault tree for an annulus pressure barrier failure in a Class I hazardous waste injection well.

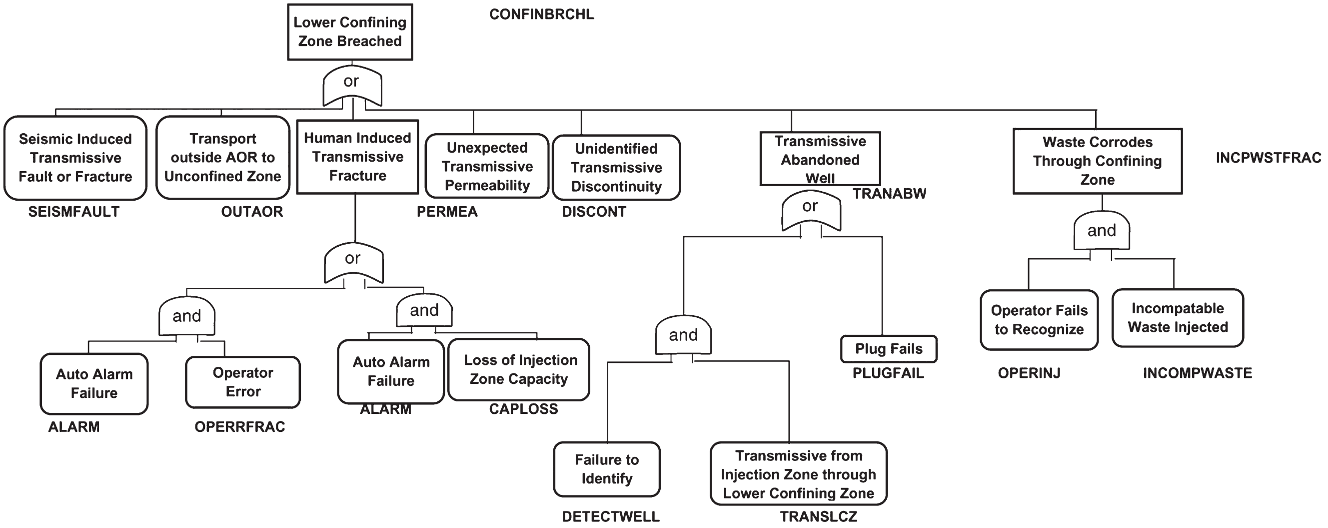

Fig. 10.4. Fault tree for a lower confining zone breach in a Class I hazardous waste injection well.

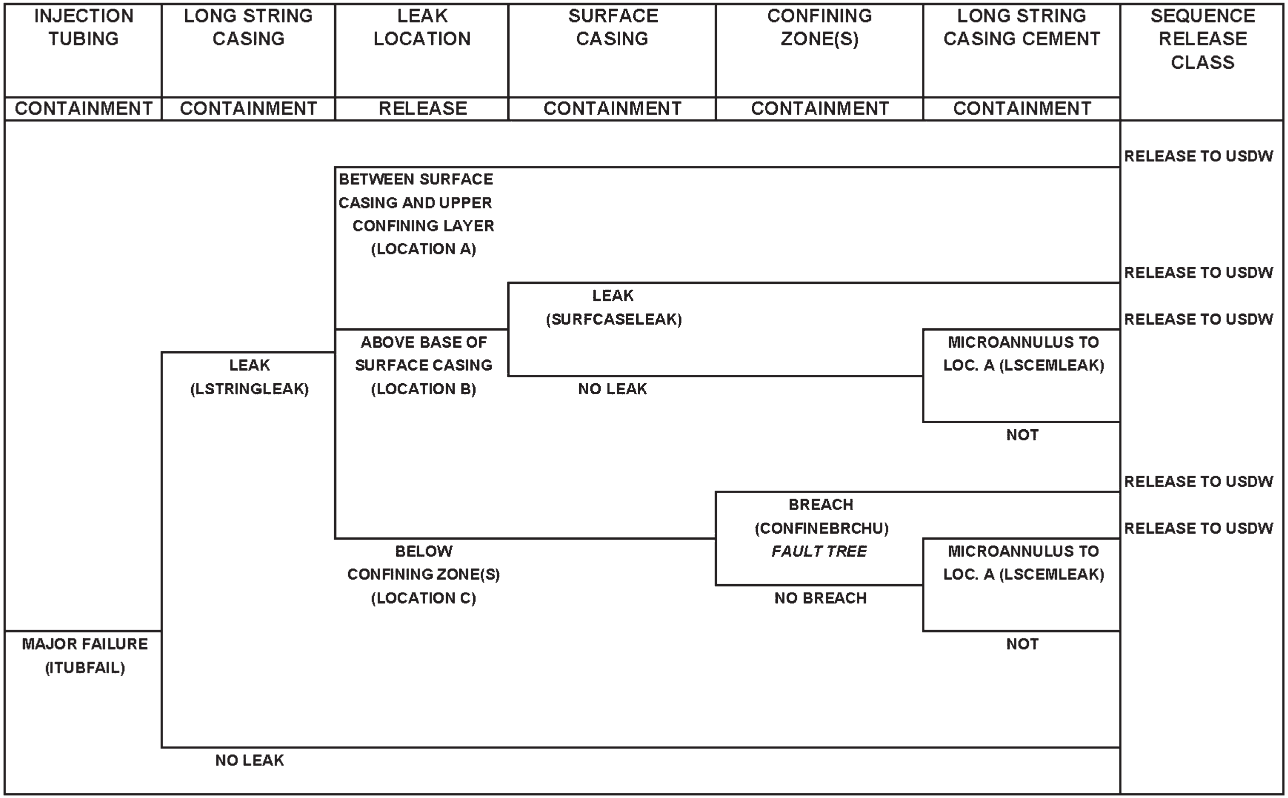

Fig. 10.5. Event tree for a major packer failure in a Class I hazardous waste injection well.

A major packer failure is a lower probability event than a packer leak. Despite this, the assumed absence of annulus pressure eliminates an important barrier to waste isolation loss and results in a higher risk than for a simple packer leak on the order of 10^{-8}–10^{-9} (see Table 10.3). With the loss of pressure, the waste is assumed to mix with the annulus fluid in the column. As above, the location of the long string casing is a critical factor in waste isolation loss, as it determines the presence or absence of additional barriers.

10.9.3 Injection Tube Leak

This initiating event involves a leak in the injection tube above the packer (see Fig. 10.6). Since it is not a catastrophic failure, annulus pressure is maintained. Aside from the location of the leak, the events and the sequence leading to containment loss is identical to that of the packer leak scenario. Similar to the packer leak, the results indicate that the probability of waste isolation loss over the life of the well is extremely low, on the order of 10^{-17}–10^{-19} (see Table 10.3). As with the packer leak, the annulus pressure is the primary barrier to loss of containment. Additionally, the location of the long string casing remains a critical factor in waste isolation loss to the accessible environment, as it determines the presence or absence of additional barriers.

10.9.4 Major Injection Tube Failure

This initiating event is similar to the major packer failure, and is characterized by a catastrophic failure of the injection tube above the packer, with the resulting loss of annulus pressure (see Fig. 10.7). Aside from the location of the failure, the sequence of events leading to possible containment loss is identical to that of the major packer failure scenario discussed above.

A major injection tube failure has a lower probability of occurring than an injection tube leak. As with the major packer failure, the assumed immediate loss of annulus pressure eliminates an important barrier to waste isolation loss and results in a higher risk than a simple leak of the injection tube, on the order of 10^{-8}–10^{-9} (see Table 10.3). With the loss of positive pressure, it is assumed that the waste mixes with the annulus fluid and escapes through the leak in the long string casing. As in all these scenarios, the location of the long string casing is a critical factor to waste isolation loss.

10.9.5 Cement Microannulus Failure

Radiotracer studies are performed annually on Class IH wells to detect migration. This event sequence involves the possibility that an extended vertical opening (i.e., microannulus) in the cement surrounding the long string casing remains undetected and results in waste isolation loss (see Fig. 10.8). The cement extends from the surface through all confining layers to the injection zone. Should a microannulus crack open in the cement, extend from the injection zone through the upper confining zone, and remain undetected, waste injected under pressure could possibly migrate up to Location A and then to the USDW. Alternatively, waste could migrate only up to a location below the upper confining zone, and then the upper confining zone could breach. An additional fault tree is needed to estimate the probability that the upper confining zone will be breached. This fault tree is presented in Figure 10.9, with the corresponding probabilities presented in Table 10.2.

The probability that loss of waste isolation will result under this scenario was calculated to be on the order of 10^{-6}–10^{-8} (see Table 10.3). The event sequence is controlled by the location

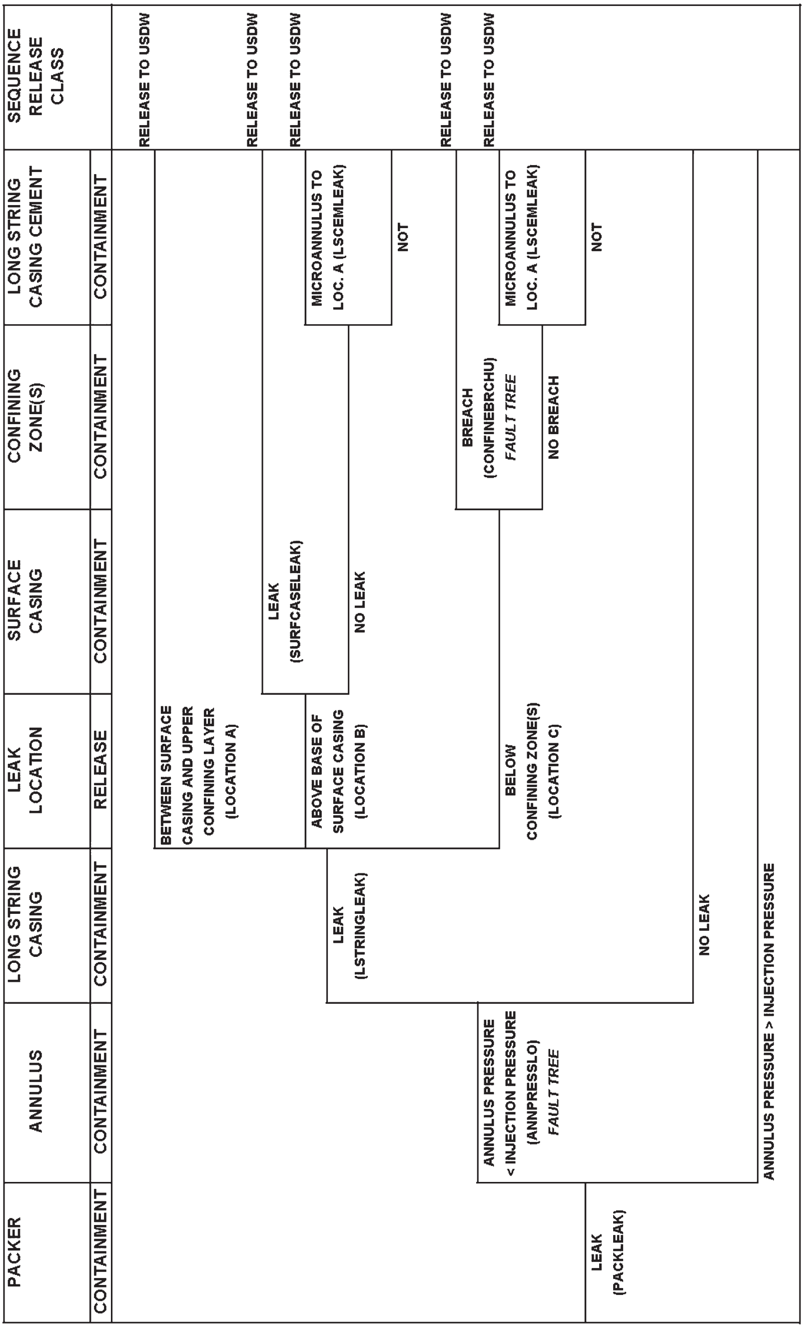

Fig. 10.6. Event tree for an injection tube failure in a Class I hazardous waste injection well.

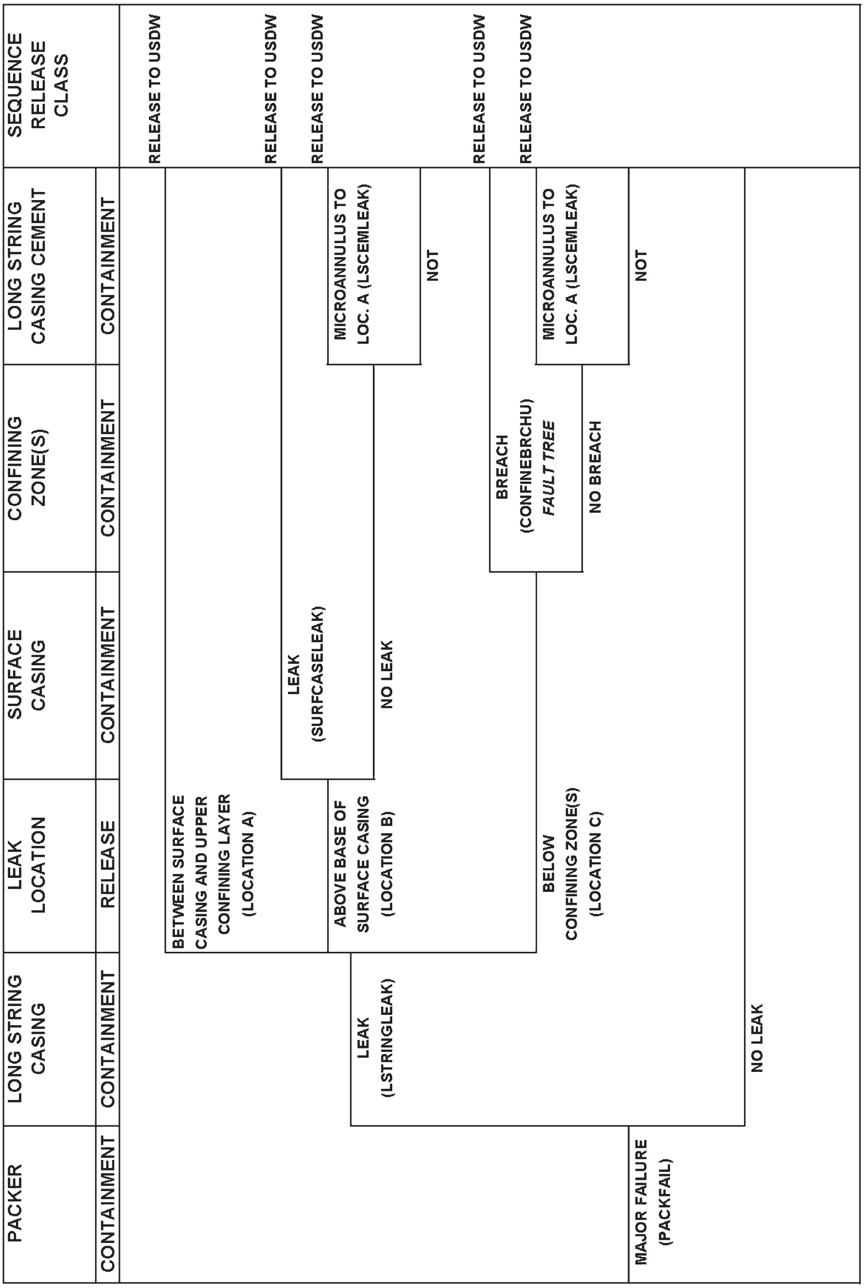

Fig. 10.7. Event tree for major injection tube failure in a Class I hazardous waste injection well.

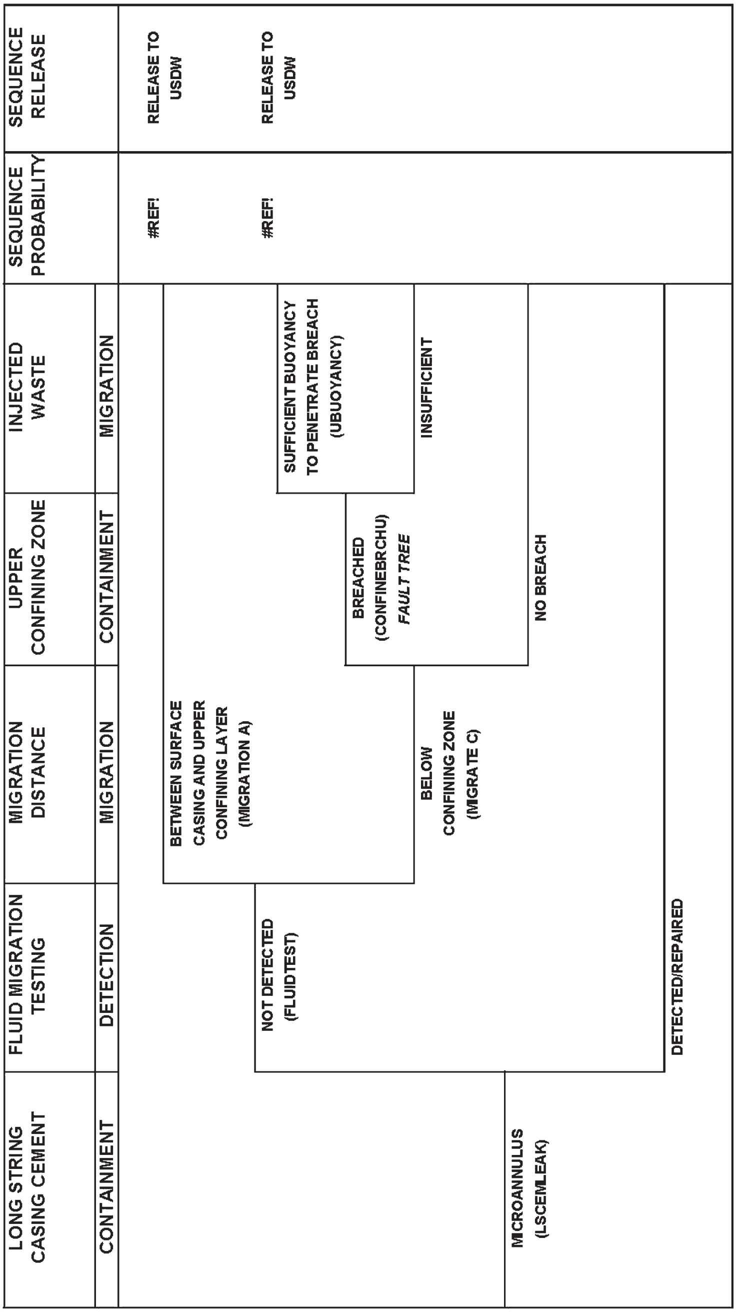

Fig. 10.8. Event tree for a cement microannulus in a Class I hazardous waste injection well.

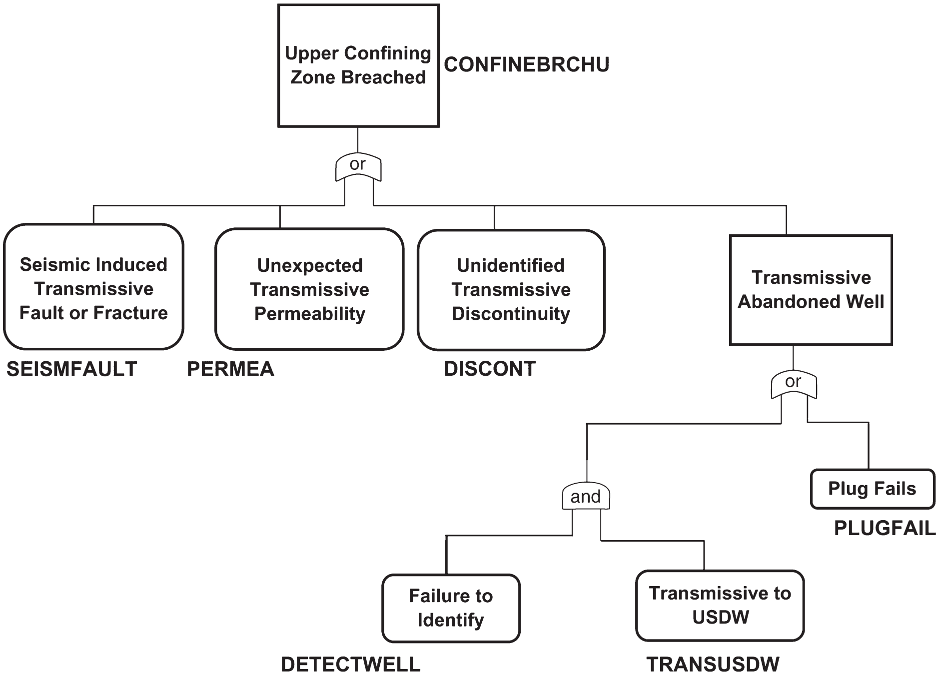

Fig. 10.9. Fault tree for upper confining zone breach in a Class I hazardous waste injection well.

to which the microannulus extends. In this case, it was assumed to extend from the injection zone to the USDW. The greatest uncertainty lies in whether such an extended and transmissive microannulus will occur, and if the waste fluid can travel that far given that the injection zone represents the path of least resistance to the pressurized waste stream. Additionally, the annual testing for fluid migration also limits the risk to loss through this mechanism.

10.9.6 Confining Zone Breach

The initiating event in this scenario is a transmissive breach of the lower confining zone (directly above the injection zone) (see Fig. 10.10). The probability of this event is based on the fault tree analysis first developed for the packer leak (see Fig. 10.4). Once the lower confining zone is breached, the remaining barriers to waste isolation loss are:

1. The waste is sufficiently buoyant to penetrate the lower confining zone breach.
2. Groundwater monitoring fails to detect waste outside of the injection zone.
3. The upper confining zone is breached.
4. The waste is sufficiently buoyant to penetrate the upper confining zone breach.

A breach in the confining zone requires that all confining zones must be completely breached with transmissive openings. This must remain undetected in spite of ongoing monitoring of pumping pressure and volumes, injection zone pressure, and groundwater quality. Additionally, the waste must have a driving force in all zones to be sufficiently buoyant to penetrate the USDW above, and there must be no bleed-off into the buffer aquifers between the confining zones. This scenario has a probability of waste isolation loss on the order of 10^{-10} (see Table 10.3).

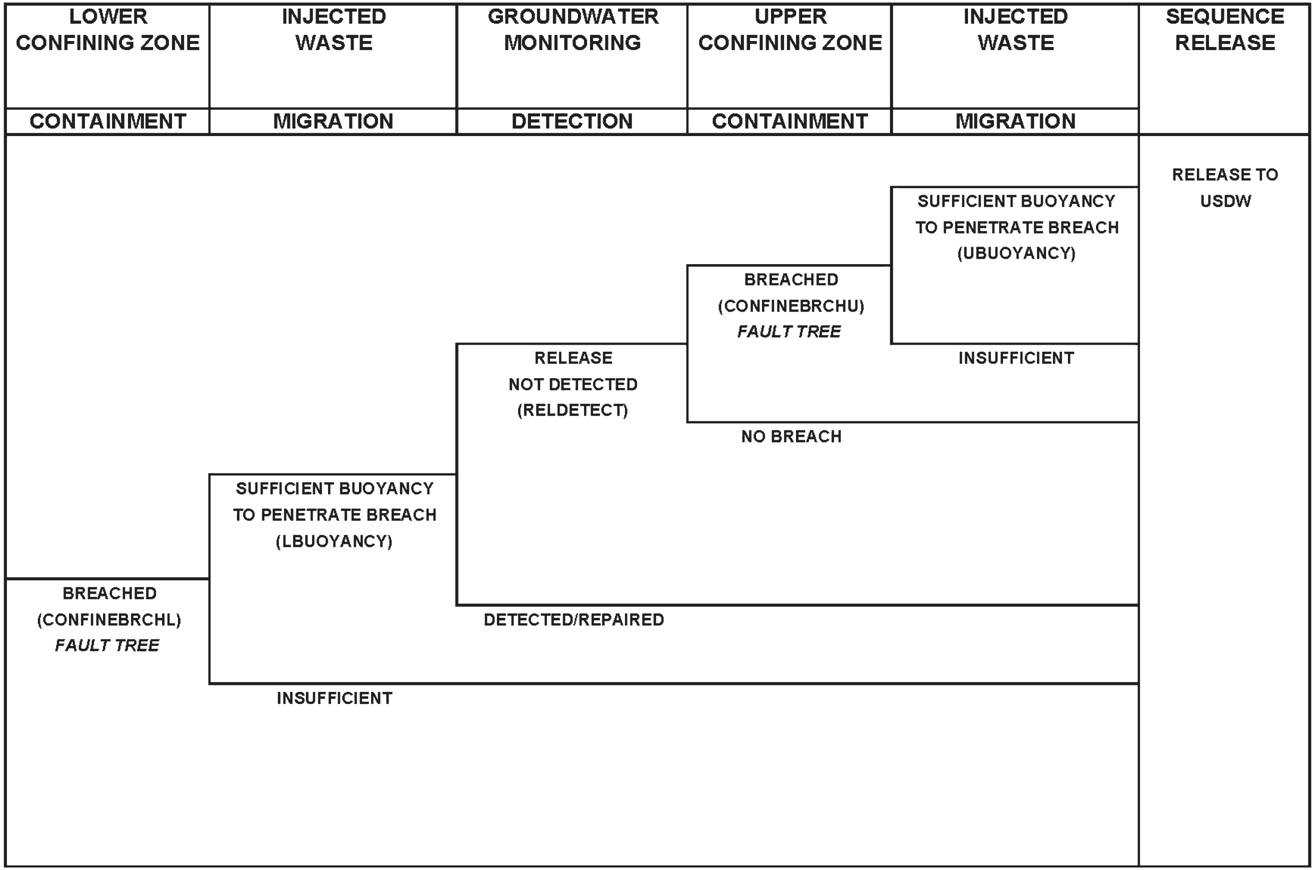

Fig. 10.10. Event tree for lower and upper confining zone breaches in a Class I hazardous waste injection well.

10.9.7 Inadvertent Injection Zone Extraction

Given the depth of most injection wells, future human intrusion into the injection zone is unlikely (see Fig. 10.11). An extraction scenario also does not rely on any additional components of the operating system. This initiating event assumes extraction of injected waste with the additional sequence probabilities included to assess the possibility that the extraction of the injection zone material goes unnoticed by the well user. The time domain is not relevant, as all such activities are assumed to have occurred after a system closure.

This scenario is the most difficult to estimate the probability of occurrence. Nonetheless, the possibility that extraction of isolated waste will occur after closure was calculated to be less than 10^{-6} (see Table 10.3). Since injection zones are more than 1000 ft deep and presumably underlie most accessible and higher quality aquifers, it is unclear why water from the injection zone would be extracted by anyone. Depending on timing and location, the waste may no longer present a potential hazard, or the plume may not be intersected by the extraction wells.

10.9.8 Incompatible Waste Injection

The issue of incompatibility of wastes and well components or geologic formations was covered under the outcomes of the other event trees. Carbon dioxide or other gas formation may result in packer blowout, rupture of the injection tube, transmissive geologic fracturing, or wellhead blowout. Each of these events are covered by the event trees for packer or injection tube failure or by the fault tree for confining zone breaches, or are considered spills and not relevant to this evaluation. Corrosion of rock or other system components are covered under the fault tree for the lower confining zone breach or the event tree for the relevant system component (i.e., injection tube leak or failure). A chemical interaction may also result in a plug forming in the system, resulting again in packer blowout, failure of the injection tube, or fractures of the different confining zones in response to a pressure buildup. These are addressed by event trees for the confining zone breach and the packer or injection tube failure, or by the fault tree for the breach of the lower confining zone.

10.10 OVERALL LOSS OF WASTE ISOLATION RESULTS

Based on the PRA conducted for Class IH wells, the 90th percentile risks for the individual scenarios detailing the potential loss of waste isolation range from a low of 10^{-17} (packer leak) to a high of 10^{-6} (cement microannulus) (see Fig. 10.12). The probability for all events combined (assuming that these risks are additive) resulting in a loss of waste isolation is between 10^{-6} and 10^{-8} (Fig. 10.12). The event sequences that are predominant contributors to overall risk are the microannulus failure and the possibility of inadvertent future injection zone extractions. The sensitivity analysis (Fig. 10.13) identified the following contributions to overall uncertainties about probability of loss of waste isolation:

- Distance that waste migrates along a vertical cement microannulus (52% of the variance).
- Likelihood of future extraction from the injection zone (17% of the variance).
- Probability that at the time of future extraction the waste is no longer hazardous or the plume is not present (15% of the variance).
- Likelihood that the fluid testing fails to detect migration (8% of the variance).
- Likelihood that the extracted material is unrecognized as waste by the well user (3% of the variance).

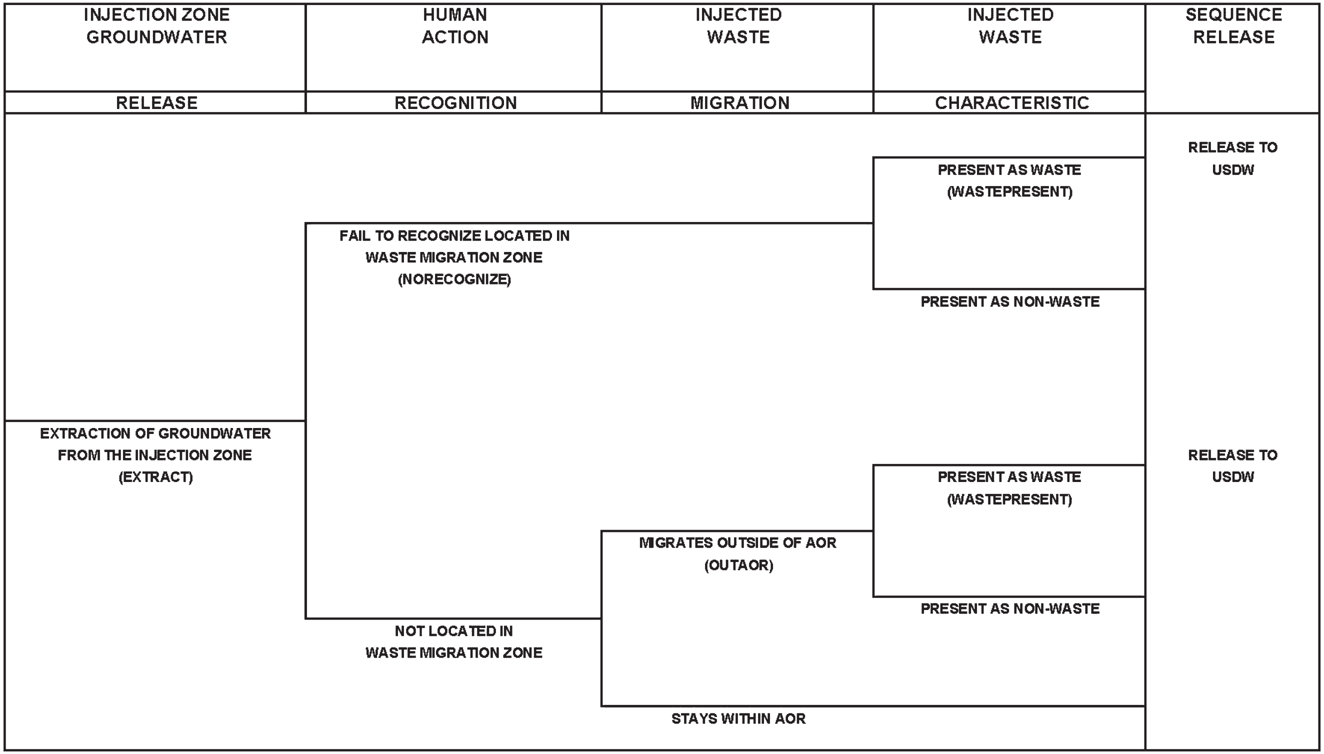

Fig. 10.11. Event tree for inadvertent extraction from an injection zone in a Class I hazardous waste injection well.

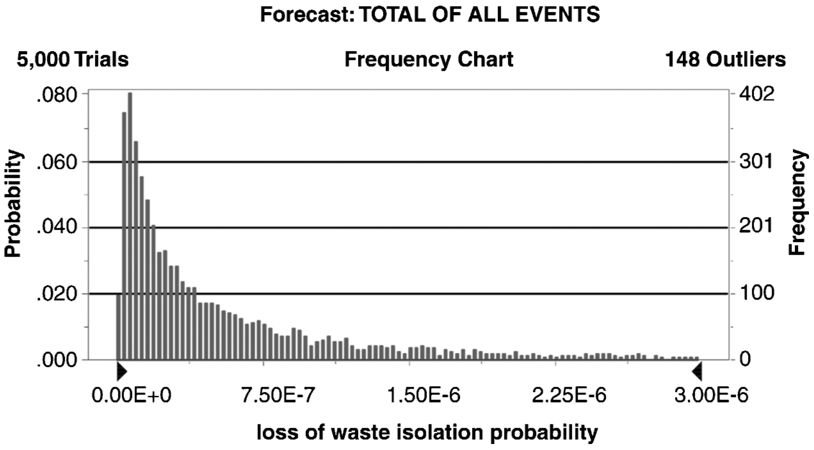

Fig. 10.12. Probability distribution for total loss of waste isolation risks in a Class I hazardous waste injection well.

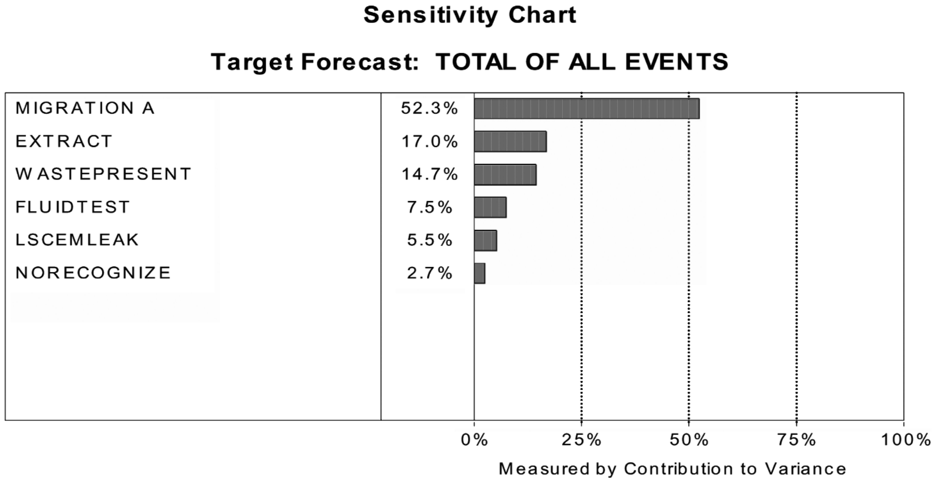

Fig. 10.13. Sensitivity chart of relative contributions to overall uncertainties for loss of waste isolation risks.

10.11 CONCLUSIONS AND RECOMMENDATIONS

Because of the conservative assumptions used for failure event probabilities and the explicit treatment given to uncertainties in this analysis, we believe that the risk of loss of waste isolation from Class IH wells is less than 10^{-6}. The low risk is due in large measure to the use of redundant engineered systems and geology to provide multiple and diverse barriers to prevent release of waste to the accessible environment. This is aided in part by the fact that deep-well injection is a simple design relying on passive systems to minimize failure modes and frequencies. The annulus pressure is a critical barrier and performance monitor, and it displays a high reliability due to the presence of automatic alarms and shutoffs, and full-time operators.

The risk of waste isolation loss is dominated by two failure scenarios:

1. The possibility that a transmissive microannulus develops in the cemented borehole outside the long string casing, and extends from the injection zone up past the geologic confining zones, and
2. The possibility of inadvertent future extraction of injected waste.

Uncertainty about the overall risk to waste isolation is also dominated by events associated with these two scenarios. For example, in developing the frequency distribution for the microannulus initiating event (LSCEMLEAK in Fig. 10.8), it was conservatively assumed that "vertical migration detected" events in the well failure database (U.S. Environmental Protection Agency, 1993) were equivalent to the occurrence of a transmissive microannulus extending from the injection zone through one or both of the confining layers; however, Class IH well operators contend that evidence of a microannulus extending from the injection zone through the confining layers has not been found. Thus, a highly uncertain event initiates the highest-risk sequence, and is therefore treated with significant conservatism in the PRA; this points to the need for more complete data on the location, duration, and length of detected microannuli, rather than just noting the number of times that vertical migration is detected.

Numerous conservative assumptions were used in this PRA that, combined with the explicit treatment of uncertainties (i.e., the Monte Carlo analysis), lend confidence to the conclusions of low risk. Credit was not taken for cement as a horizontal barrier to waste migration. Likewise, in using the well failure database (U.S. Environmental Protection Agency, 1993), all events termed "failure" for packers, tubing, and casing were assumed to be breaches of sufficient size and duration to transmit waste. As explained above, "vertical migration detected" events were similarly assumed to represent a complete transmissive pathway from the injection zone, and up past the geologic confining layer(s). In the event of a breach of the confining layers, the buoyancy of the waste and the injection pressure were assumed to be high enough to drive migration through breaches of multiple confining layers. Significant bleed-off and attenuation that would occur in the intervening buffer aquifers were not taken into account. Only two geologic confining layers were assumed throughout this PRA, although survey information indicates that three or more confining zones are usually present. Published human-error data were used as the lower bound on probability distributions for events that assumed an equal probability for error rates to be an order of magnitude higher than published rates. While automatic shutdown of the injection well pumps is a typical operating feature of most Class IH wells, no automatic shutdown was assumed for this PRA. It was further assumed that a release between the surface casing and the upper confining zone was equivalent to a release to the USDW, and that releases below the confining zones involved only one confining zone barrier to the USDW. Finally, the timing between independent occurrences in the various event and fault trees was assumed to be coincident for sufficient duration prior to detection and corrective action for a release to the USDW to occur.

Since the failure location and timing of the individual events are critical to the development of these release scenarios, uncertainty would be reduced and knowledge improved if this information were collected and included in the databases maintained on Class I well failures. The presence, degree of training, and diligence of the operator is important in preventing system failure and loss of waste isolation. This is especially critical in maintaining the annulus pressure, which is a major barrier to loss of waste from the system. Uncertainty over the existence and transmissivity of extended vertical cement breaches is important. Experimental or field data on the microannulus assumed to exist in these scenarios would assist in reducing this uncertainty and improving the risk estimates. Finally, we recommend that future assessments of the potential environmental risks associated with deep-well injection explicitly take into account the probability of release and the amount of waste that could be released by the mechanisms of feasible system failure scenarios.

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APPENDIX: BASIS FOR EVENT FREQUENCY PROBABILITY DISTRIBUTIONS

There are 42 events identified in the PRA (Table 10.2) for which failure rates are needed to calculate event- and fault-tree probabilities. For many of these events, occurrence is so rare and data are so sparse that a confident point estimate for the frequency of occurrence cannot be established. Directly applicable data on the frequency of most events were not found. In common practice, most component failure modes are identified and corrected during required testing and maintenance, and thus may not be recorded as a failure event per se. More than one-third of the events involved some type of human error. Human error frequency data are available (Swain and Guttman, 1980; Swain, 1987); however, their direct applicability to the human tasks involved in Class IH wells is uncertain.

Consequently, uncertainty about occurrence frequencies was given explicit quantitative treatment in the PRA. Probability distributions of event occurrence frequencies were developed, either based on available occurrence data or expert judgment. In general, probability distributions for event frequencies were derived as follows:

1. A 1993 EPA reply to a House of Representatives subcommittee inquiry (U.S. Environmental Protection Agency, 1993) provided state-by-state summaries of certain

reported types of Class I injection well failure events between 1988 and 1992. Numbers of events were reported for 469 Class I wells (hazardous and nonhazardous) located in 12 states. Events reported included tubing, casing, and packer leaks; and waste migration on the outside of the long string casing (i.e., cement microannulus). The number of reported events was divided by 855,925 well days (469 wells × 5 yr × 365 days/yr) to derive an estimate of the average daily occurrence rate for each type of event. Because nonhazardous wells have less regulatory restrictions than hazardous, it was a conservatism to include these data.

2. Modeling these failure rates with a binomial distribution, it is possible to determine the confidence intervals for a given average failure rate. Estimations of the 90th percentile upper confidence limit of the average failure rates were calculated using methods outlined by McCormick (1981). These are shown in Table A.1.

Table A.1.

Component	Number of reported failures	90th percentile confidence limit of average failure rate (day^{-1})
Tube	48	6.80E–05
Casing*	28	4.20E–05
Packer*	31	4.60E–05
Waste migration†	5	1.10E–05

*Three recorded “annulus leak” events were included because it could not be determined if these were casing- or packer-related.

†This category is assumed to be a surrogate for casing cement leak events.

Probability distributions representing uncertainties about frequency rates of these events (ITUBLEAK, LSTRINGLEAK, PACKLEAK, LSCEMLEAK) were developed by using these upper confidence limits for the average rate as the rate parameter in a Poisson distribution. The Poisson distribution is commonly used in reliability analyses to describe random failures in a system that cause irreversible transitions in the system (Clemen, 1991) such as a loss of waste isolation. The Poisson distribution requirements (Clemen, 1991), which are met for this application, include:

- Events can happen at any time within the day.
- The probability of an event is small.
- Events can happen independently of other events.
- The average number of events per day does not change with time.

3. For events involving typical components of any industrial system, such as valve, pump, control system, or alarm failures, occurrence frequencies were obtained from available industrial reliability databases (Davis and Satterwhite, 1988; Envirosphere Company, 1988; Lannoy and Procaccia, 1996).
4. Most human-error rates were derived from available human reliability data for similar activities. Usually, these human error data have been compiled for highly trained and scrutinized occupations such as nuclear power plant operators (Swain and Guttman, 1980; Swain, 1987) and firemen (Davis and Satterwhite, 1988; Envirosphere Company, 1988). While Class I hazardous waste injection well operators arguably fall into this same category, this assessment conservatively assigned human-error rates as the lower bound of the distribution, with an upper bound set at a higher order of magnitude.

5. For events in which data are entirely lacking, the authors relied on professional judgment, shaped in part by the experience of deep-well operators and regulators elicited during workshops held in conjunction with Ground Water Protection Council national meetings. To account for uncertainty in professional judgment, relatively large bounds of uncertainty were applied to frequencies derived in this manner. When the uncertainty was high, the range of the distribution would span several orders of magnitude. In some cases, the frequency was set at a maximum value; for example, the probability that injected fluid is sufficiently buoyant to penetrate a lower confining zone breach was assumed to be 1.

The probability distributions representing uncertainty about event frequencies are summarized in Table 10.2 of the chapter and discussed individually below.

Event: ITUBLEAK
Description: Injection tube leak.
Probability: Poisson distribution with 6.8E–05/day rate.
Basis: This event quantifies the probability that the injection tube carrying waste to the injection zone will develop a leak. Based on compilation of state-by-state data analyzed as discussed above.

Event: ITUBFAIL
Description: Sudden major failure and breach of the injection tube.
Probability: 1/100th of ITUBLEAK probability.
Basis: ITUBFAIL assumes a sudden and major failure of the injection tube such that the annulus pressure is lost simultaneously. Based on professional judgment, the likelihood of the injection tube failing catastrophically was estimated to be 1/100th the probability of a leak. Thus the ITUBFAIL probability was assigned a value 0.01 times the ITUBLEAK probability.

Event: ANNPRESSLO
Description: Annulus pressure drops below injection pressure.
Probability: Determined by fault tree analysis.
Basis: Due to the multiple components associated with this failure event, an ANNULUS PRESSURE BARRIER FAILURE FAULT TREE (Fig. 10.3) was developed and used to evaluate the event probability. The resulting cumulative distribution for this event frequency is:

10th percentile	1.5E–12
20th percentile	2.6E–12
30th percentile	3.8E–12
40th percentile	5.2E–12
50th percentile	7.0E–12
60th percentile	9.3E–12
70th percentile	1.2E–11
80th percentile	1.7E–11
90th percentile	2.4E–11

Event: LSTRINGLEAK
Description: Long string casing leak.
Probability: Poisson distribution with 4.2E–05/day rate.
Basis: Based on compilation of state-by-state data analyzed as discussed above.

Event: LSCASEFAIL
Description: Sudden and major failure and breach of the long string casing.
Probability: 1/100th of LSTRINGLEAK probability.
Basis: LSCASEFAIL assumes a sudden and major failure of the long string casing such that the annulus pressure is lost simultaneously. Based on professional judgment, the likelihood of the long string casing failing catastrophically was estimated to be 1/100th the probability of a leak. Thus the LSCASEFAIL probability was assigned a value 0.01 times LSTRINGLEAK.

Event: SURFCASELEAK
Description: Surface casing leak.
Probability: Poisson distribution with 4.2E–06/day rate.
Basis: The surface casing surrounds the long string casing and provides one of the final engineered barriers to the USDW. Failure probabilities are derived from LSTRINGLEAK with a correction of 0.1 to account for the fact that the surface casing is subject to less stress than the long string casing, and it is shorter and closer to the surface, making it less likely to be subject to construction failure modes.

Event: LSCEMLEAK
Description: Long string casing cement microannulus allows fluid movement along casing.
Probability: Poisson distribution with 1.1E–05/day rate.
Basis: Surrounding the entire length of the long string casing is cement, which fills the void between the casing and the surrounding geology. Given that there may be discontinuities in the cement pack, there is the probability that waste may migrate up the outer length of the casing through a microannulus discontinuity in the cement. Based on the state-by-state data responses for "waste migration," a failure rate parameter for the distribution was determined using the methodology described above.

Event: LOCATION A
Description: Long string casing leak is located between surface casing and uppermost confining zone.
Probability: Uniform distribution from 1.0E–02 to 5.0E–02.
Basis: Given that a long string casing leak has occurred, the exact location along its entire length determines the likely migration route. If the leak occurs within the bounds defined by LOCATION A, migration to the USDW is assumed to be immediate and complete. Estimation of probability is based on professional judgment and takes into account the length of casing in this location relative to the typical overall long string casing length. In addition, consideration was given to the fact that stresses on the casing increase with depth.

Event: LOCATION B
Description: Long string casing leak is located above the bottom of the surface casing.
Probability: Uniform distribution from 1.0E–02 to 1.0E–01.
Basis: The same logic applied to the determination of LOCATION A probability is used here.

Event: LOCATION C
Description: Long string casing leak is located below the confining zone(s).
Probability: 1-Prob(LOCATION A)–Prob(LOCATION B).
Basis: The final section of the casing string extends from the top of the uppermost confining zone to the injection zone. This represents the largest fraction of the casing length, and stresses increase with depth, so the likelihood for a casing leak is higher in this location. Given that a long string casing leak has occurred, the probabilities for LOCATION A, LOCATION B, and LOCATION C must sum to unity. Thus, an algorithm is included in the event tree for the Monte Carlo simulation that calculates the probability of LOCATION C based on the probabilities selected at each iteration for LOCATION A and LOCATION B.

Event: MIGRATION A
Description: Waste migrates up the microannulus to Location A between the surface casing and the upper confining zones.
Probability: Uniform distribution from 1.0E−04 to 1.0E−02
Basis: Radiotracer studies are performed annually on Class IH wells to detect migration. It is assumed that these studies do not always detect the formation of an extended vertical opening, i.e., a microannulus, in the cement surrounding the long string casing. If a microannulus extends from the injection zone through the upper confining zone, waste under pressure could migrate to Location A, and ultimately to a USDW. The probability of loss of waste isolation by this scenario is calculated to be on the order of 10^{-6} to 10^{-8}.

Event: PACKLEAK
Description: Packer leak.
Probability: Poisson distribution with 4.6E–05/day rate.
Basis: This event quantifies the probability that the packer will develop a leak. The packer seals the bottom of the annulus between the long string casing and the injection tube. The probability is based on compilation of state-by-state data analyzed as discussed above.

Event: PACKFAIL
Description: Sudden and major failure and breach of packer.
Probability: 1/100th of PACKLEAK probability.
Basis: Using the same basis applied to other catastrophic failure events, a professional judgment of 1/100th of the probability of a leak was used for complete packer failure.

Event: FLUIDTEST
Description: Testing fails to detect injection fluid migration along outside of long string casing.
Probability: Uniform distribution from 5.0E–04 to 5.0E–03.
Basis: Regular testing is required to detect migration fluid along the outside of the casing material. Generally, the probability of failing to detect a leak is most likely due to operator error, either in the procedure or in the interpretation of results. Thus, the probability of failing to detect fluid migration is based

on the probability of operator—hence, human error. Studies prepared for nuclear power plant reliability analyses (Swain and Guttman, 1980; Swain, 1987) are primary sources for human-error rates. These studies show that errors of omission for nonpassive tasks (maintenance, test, or calibration) occur at a rate of approximately 1.0E–03 per demand, with a range from 5.0E–04 to 5.0E–03. It is assumed that a single failure to detect on demand (i.e., at the time of the test) results in significant fluid migration.

Event: CONFINEBRCHL
Description: Transmissive breach occurs through lower confining zone.
Probability: Determined by fault tree analysis.
Basis: Due to the multiple components associated with this failure event, a LOWER CONFINING ZONE BREACH FAULT TREE (Fig. 10.4 in chapter) was developed and used to evaluate the event probability. The resulting cumulative distribution for this event frequency is:

10th percentile	1.7E–03
20th percentile	1.9E–03
30th percentile	2.2E–03
40th percentile	2.5E–03
50th percentile	2.9E–03
60th percentile	3.4E–03
70th percentile	4.3E–03
80th percentile	5.8E–03
90th percentile	8.2E–03

Event: CONFINEBRCHU
Description: Transmissive breach occurs through upper confining zone.
Probability: Determined by fault tree analysis.
Basis: Due to the multiple components associated with this failure event, an UPPER CONFINING ZONE BREACH FAULT TREE (Fig. 10.9) was developed and used to evaluate the event probability. The resulting cumulative distribution for this event frequency is:

10th percentile	1.6E–03
20th percentile	1.8E–03
30th percentile	2.1E–03
40th percentile	2.4E–03
50th percentile	2.7E–03
60th percentile	3.3E–03
70th percentile	4.2E–03
80th percentile	5.6E–03
90th percentile	7.9E–03

Event: LBUOYANCY
Description: Injection fluid is sufficiently buoyant to penetrate the lower confining zone breach.
Probability: 1.0

Basis: Because fluid is being injected under pressure below the lower confining zone, it is conservatively assumed that this provides sufficient buoyancy to penetrate a breach. In general, in the absence of active injection pressure, it is unlikely that buoyancy would be sufficient to transmit injected fluid completely through a breach.

Event: UBUOYANCY
Description: Injection fluid is sufficiently buoyant to penetrate upper confining zone breach.
Probability: Uniform distribution from 1.0E–05 to 1.0E–04.
Basis: It is assumed that fluid injection would need to be maintained (while losing pressure to the breach in the confining zones) or even overpressurized to provide a sufficient force to drive fluid through breaches in both the lower and upper confining zones. For this to occur, there would need to be an operator error in failing to detect an injection pressure loss or overpressurization. As explained above, human reliability data show that errors of omission for nonpassive tasks occur within a range of 5.0E–04 to 5.0E–03 per demand. While pressure is checked continuously during injection, it is conservatively assumed that a single failure to detect a pressure change results in significant fluid movement up through the breaches.

Event: RELDETECT
Description: Groundwater monitoring fails to detect waste release outside injection zone.
Probability: 0.5
Basis: This probability is based on professional judgment. Given a release of waste fluid through postulated confining zone breaches, required groundwater monitoring should detect a release. When the release is detected, the injection would be ceased, and the driving force for upward fluid movement would be eliminated. This sequence could fail if the monitoring locations are not at or down gradient of the location of the breach in the confining zone, or if the time between release and detection is long enough that a significant release occurs before corrective action is taken.

Event: EXTRACT
Description: Extraction of groundwater from same saturated zone as injection zone.
Probability: Uniform distribution from 1.0E–05 to 1.0E–03.
Basis: This probability is based on professional judgment. Deep-well injection zones contain nonpotable water, usually of high salinity, with no attractive resource value. A number of more useful water-bearing zones occur at shallower depths that can be accessed much more cost-effectively. The probability of this event occurring near an existing or former deep-injection well at any time in the foreseeable future is considered to be very low.

Event: NORECOGNIZE
Description: Failure to recognize that groundwater extraction is located within injected waste plume.

Probability: Uniform distribution from 1.0E–03 to 1.0E–02.

Basis: Assuming that someone in the future screens an extraction well at injection zone depth, there is the probability that they do not recognize the well has intercepted an injected waste plume. This event would require both the failure to recognize that the well is located within a documented Class I hazardous waste injection well AOR and that the extracted water contains waste. The distribution is based on professional judgment, taking into consideration significant uncertainties associated with time frames in the thousands of years as well as the small area of the plume relative to the entire saturated zone.

Event: OUTAOR

Description: Injection waste has migrated outside the AOR to an unconfined zone.

Probability: Uniform distribution from 1.0E–05 to 1.0E–04.

Basis: Migration of the injected waste plume outside the AOR is assigned a low probability of occurrence given the extensive characterization efforts required for the no-migration petition. It is conservatively assumed in the PRA that if this event occurs and the injected material is still characteristically hazardous, then a release to a USDW occurs. Horizontal and upward migration of injected fluid far from predicted ranges would be necessary for this to occur.

Event: WASTEPRESENT

Description: Injected waste has not transformed into nonwaste.

Probability: Uniform distribution from 1.0E–02 to 1.0.

Basis: This event addresses the probability that injected waste has not transformed into a nonhazardous form at a future time when either (a) groundwater is inadvertently extracted from the injected waste plume or (b) the plume has migrated outside the AOR to an unconfined zone. The assigned probability distribution takes into consideration (a) it is not uncommon to render the waste nonhazardous by pretreatment and dilution prior to or during injection, (b) injected waste attenuates in the plume, and (c) biodegradation and other transformation/loss processes may decrease hazardous constituents over time. Inadvertent extraction and migration outside the AOR are events with long time frames, and there is reasonable likelihood that these factors could have transformed the waste by the time of these event sequences.

Event: PUMPPA

Description: Annulus pump fails.

Probability: Triangular distribution with min = 5.0E–05; mode = 3.0E–04; max = 5.0E–03.

Basis: The European Industry Reliability Data Bank (Lannoy and Procaccia, 1996) provides a resource of compiled data for equipment failure rates. Based on the failure rates per hour (5.0E–07 to 5.0E–04) for pumps with long operating times, the daily (assuming a 10 hour daily operating period) probability of pump failure is between 5.0E–06 and 5.0E–03 day^{-1}. These data are generally supported by similar mechanical failure rates from

PRAs performed for the nuclear power industry. Range estimates for pump failures from a number of nuclear industry resources (McCormick, 1981) provide a median value of 3.0E–05 failures/hour (3.0E–04 failures/day). For the nuclear industry, redundancies and routine replacement ensure that the failure rates and consequences of pump failure are minimal. A triangular distribution was used for annulus pump failure rates, using the nuclear power industry value of 3.0E–04 failures/day as the mode and assigning the European database values as the extreme range values.

Event: CHECKPA
Description: Annulus check value fails to open.
Probability: Triangular distribution with min = 1.0E–04; mode = 3.0E–04; max = 1.0E–03.
Basis: Given that the annulus pump fails, CHECKPA is the probability that the check valve, designed to keep the annulus fluid contained and pressurized in the annulus, stays open. This is an on-demand failure rate in that failure only occurs when the component is called to function. Data from McCormick (1981) give an on-demand failure rate for check values (fail to open) of 1.0E–04 to 1.0E–03 per demand (median of 3.0E–04). Because CHECKPA is conditional upon PUMPPA, and both are represented by the same AND gate within the fault tree, the on-demand probability is used directly.

Event: CONTROLPA
Description: Annulus pressure control system fails, resulting in underpressurization.
Probability: Uniform distribution from 1.0E–06 to 1.0E–04.
Basis: Control system failures are usually the result of electronic or electrical failures resulting from loss of signal function. Lannoy and Procaccia (1996) list the range of electrical/electronic failures from the compiled databases to be between 5.00E–08 and 1.00E–05 hour^{-1}. For a one-day operating period, this range converts in to a failure probability of 1.2E–06–2.4E–04 day^{-1}. Since this range has no point of central tendency, a uniform distribution is selected for the PRA.

Event: CONTROLPI
Description: Injection pressure control system resulting in overpressurization.
Probability: Uniform distribution from 1.0E–06 to 1.0E–04.
Basis: This is a similar control system failure, as was described for CONTROLPA. Similar logic is used to specify a probability distribution.

Event: OPERRPA
Description: Operator error causes annulus pressure to drop below injection pressure.
Probability: Uniform distribution from 5.0E–05 to 5.0E–04.
Basis: Swain (1987) provides data on human error, showing a frequency of 1.0E–05 error per action. Assuming the operator is performing five critical actions per day that could lead to a potential pressure drop, the daily failure rate is 5.0E–05. A uniform distribution that assumes this estimate is that lower bound was used; it is equally likely to be up to an order of magnitude of higher frequency of human error. Since all operator errors in this

PRA may be performed by either the same or a similarly trained operator, this and the other operator error event probability distributions were correlated in the Monte Carlo simulation using a correlation coefficient of 0.5.

Event: OPERRPI
Description: Operator error causes injection pressure to rise above annulus pressure.
Probability: Uniform distribution from 5.0E–05 to 5.0E–04.
Basis: The same basis applies as for event OPERRPA, above.

Event: OPERRDET
Description: Operator fails to detect/respond to unacceptable pressure differential.
Probability: Uniform distribution from 5.0E–05 to 5.0E–04.
Basis: The same basis applies as for event OPERRPA, above.

Event: OPERRFRAC
Description: Operator error results in induced transmissive fracture through lower confining zone.
Probability: Uniform distribution from 5.0E–05 to 5.0E–04.
Basis: The same basis applies as for event OPERRPA, above.

Event: OPERINJ
Description: Operator fails to recognize changes in confining zone capacity.
Probability: Uniform distribution from 5.0E–05 to 5.0E–04.
Basis: The same basis applies as for event OPERRPA, above.

Event: CAPLOSS
Description: Loss of injection zone capacity results in overpressurization.
Probability: Uniform distribution from 1.0E–05 to 1.0E–03.
Basis: The capacity of injection zone rock is carefully studied for a Class I well as part of the site-selection process and no-migration petition. Given the extent of the characterization efforts involved, it is unlikely that a lack of capacity will be overlooked. This would be the result of a human error of omission, which occurs at a rate of approximately 1.0E–03 per demand. Because at least one additional independent review of this factor would be performed (e.g., by the regulatory agency), this frequency is assumed to be the upper bound of the distribution.

Event: PERMEA
Description: Confining zone has unexpected transmissive permeability.
Probability: Uniform distribution from 1.0E–05 to 1.0E–03.
Basis: The permeability of confining zone rock is carefully studied for a Class I well as part of the site-selection process and no-migration petition. Given the extent of the study efforts involved, it is unlikely that permeability will be incorrectly characterized. This would be the result of a human error of omission, which occurs at a rate of approximately 1.0E–03 per demand. Since at least one additional independent review of this factor would be performed (e.g., by the regulatory agency), this frequency is assumed to be the upper bound of the distribution.

Event: DISCONT
Probability: Uniform distribution from 1.0E–04 to 1.0E–02.
Description: Presence of unidentified transmissive discontinuity.
Basis: As per the discussion on the characterization efforts outlined above for PERMEA, it is unlikely that the geologic properties of the confining zone were not completely described. However, irregularities in the geological characteristics of the confining zone are possible, given the lateral extent of the injection zone. Thus a factor of 10 higher probability than was assigned to PERMEA was used.

Event: DETECTWELL
Description: Failure to identify abandoned well in AOR.
Probability: Uniform distribution from 1.0E–03 to 1.0E–02.
Basis: Based on similar arguments used for PERMEA and DISCONT, it is unlikely that the presence of abandoned wells within the AOR would remain undetected. However, records for abandoned wells could be missing or incorrect. The distribution range used is higher in error frequency to reflect this added consideration.

Event: ALARM
Description: Automatic alarm fails.
Probability: Uniform distribution: 1.00E–05 to 1.00E–03.
Basis: The frequency of alarm failures were analyzed by Davis and Satterwaite (1988) for fire hazards associated with the management and storage of radioactive waste. A failure probability of 5.00E–05 was determined. However, this assessment was based on alarms with high-reliability requirements specified for nuclear facilities. To account for the possibility that less-reliable equipment might exist at an injection well facility, this value was used as the lower bound of a uniform distribution that includes an equal probability that the alarm failure rate could be as much as a factor of 100 higher.

Event: SEISMFAULT
Description: Seismic event induces a transmissive fault or fracture.
Probability: Uniform distribution: 1.00E–05 to 1.00E–04.
Basis: Avoidance of areas prone to seismic activity is carefully studied for a Class I well as part of the site-selection process and no-migration petition. In addition, seismic factors are part of the design criteria for the well. Given the extent of the study efforts involved, it is unlikely that the well will be located where seismic activity has been incorrectly characterized. The event would more likely be a rare event that heretofore had not occurred at such a magnitude in the region of the well site, and therefore is not reflected in historical seismic event data. In addition, the seismic event would need to result in a transmissive fault or a fracture penetrating entirely the confining zone. This event was assigned, by judgment, a probability of occurrence in the range of 1 in 100,000 to 1 in 10,000.

Event: PLUGFAIL
Description: Identified abandoned well plug fails.
Probability: Poisson distribution with 8E–04/well rate.
Basis: Assignment of failure probability is based on TRC proper plug hearing files in Clark (1987). In this study, 2531 oil and gas fields were examined for plug leakage incidents in abandoned wells. Two leakage incidents were found. The number of abandoned wells could exceed the number of fields by a factor of 10. A conservative failure rate was estimated as 2 plug failures per 2531 fields, or 8E–04 plug failures per abandoned well (assuming only one well per field). Since this event meets the Poisson distribution requirements (see above in introductory remarks), a Poisson distribution was assumed using the failure rate determined here.

Event: TRANSUSDW
Description: Unidentified abandoned well is transmissive through upper confining zone to USDW.
Probability: 0.1
Basis: There are no data on which to base this event frequency. The assumed probability of 0.1 assumed is believed to be very conservative considering that the event requires the abandoned well to provide a pathway, other than plug failure, to transmit injected waste through the entire confining zone.

Event: TRANSLCZ
Description: Unidentified abandoned well is transmissive from injection zone through lower confining zone.
Probability: 0.1
Basis: There are no data on which to base this event frequency. The assumed probability of 0.1 is believed to be very conservative considering that the event requires the abandoned well to provide a pathway, other than plug failure, to transmit injected waste through the entire confining zone.

Event: INCOMPWASTE
Description: Injected waste is incompatible with previously injected material.
Probability: Uniform distribution from 1.00E–05 to 1.00E–04.
Basis: Material that is injected is well characterized to ensure that no chemical or physical reactions that could sufficiently alter the properties of the material in the injected zone take place. In addition, the no-migration petition process requires study of waste–host rock compatibility. This event also assumes sufficient waste volume and reaction with the confining-zone rock to result in a complete breach of the confining zone. This event was assigned, conservatively by judgment, a probability of occurrence in the range of 1 in 100,000 to 1 in 10,000.