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Economic Analysis of the South Pole Traverse

James H. Lever and Paul Thur

May 2014



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Economic Analysis of the South Pole Traverse

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Final Report

Approved for public release; distribution is unlimited.

Prepared for National Science Foundation, Division of Polar Programs,
Antarctic Infrastructure and Logistics
Arlington, VA 22230

Under Engineering for Polar Operations, Logistics, and Research (EPOLAR)
EP-ANT-12-05, "SPoT Mobility Field Support"

Abstract

The U.S. Antarctic Program (USAP) operates the South Pole Traverse (SPoT) to resupply Amundsen-Scott South Pole Station from McMurdo Station. During its first three operational seasons (2008–2011), SPoT's eight tractors delivered an average annual payload of 768,000 lb, most of which was fuel traveling in high-efficiency bladder sleds. These deliveries offset an average of 30 annual LC130 flights to South Pole.

We present here an economic analysis of the payback achieved by SPoT during its first three seasons. Costs include SPoT annualized capital and annual operating expenses, and benefits are reduced LC130 costs apportioned per round-trip to South Pole. SPoT's net economic benefits of \$2.0M/year result from significantly lower delivery costs per pound compared with LC130 airlift (\$3.60/lb versus \$6.10/lb, respectively). Additional benefits of SPoT include reduced air emissions, ability to transport outsized or overweight cargo, and increased availability of LC130s to support other science operations in Antarctica.

The results here are structured to guide future USAP investments. For example, sled-efficiency improvements dramatically boost benefits: performance gains from using black rather than tan bladders could increase SPoT's annual fuel delivery per round trip by 58% and more than double its net economic benefits to \$4.6M/year.

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Preface

This study was conducted for the National Science Foundation (NSF), Division of Polar Programs (PLR), Antarctic Infrastructure and Logistics under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-12-05, “SPoT Mobility Field Support.” The technical monitor was George L. Blaisdell, Chief Program Manager, U.S. Antarctic Program, NSF-PLR.

The work was performed by Dr. James Lever (Force Projection and Sustainment Branch, Edel Cortez, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), and Paul Thur, Traverse Operations Manager, Lockheed Martin–Antarctic Support Contract (LM-ASC). At the time of publication, Dr. Justin Berman was Chief of the Research and Engineering Division. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

The authors thank G. L. Blaisdell and J. C. Weale for their helpful reviews of the manuscript. We also thank the South Pole Traverse field crews for their dedication and hard work to make SPoT an important contribution to the U.S. Antarctic Program.

The Commander of ERDC is COL Jeffrey R. Eckstein, and the Director of ERDC is Dr. Jeffery P. Holland.

Acronyms and Abbreviations

ACL	Allowable Cabin Load
AMC	Air Mobility Command
ASC	Antarctic Support Contract
AW	Airlift Wing
CEE	Comprehensive Environmental Evaluation
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
DOD	Department of Defense
EPA	U.S. Environmental Protection Agency
GrIT	Greenland Inland Traverse
HMW-PE	High Molecular Weight Polyethylene
MOA	Memorandum of Agreement
NDCF	National Defence and the Canadian Forces
NSF-PLR	The National Science Foundation's Division of Polar Programs
NYANG	New York Air National Guard
p.a.	Per Annum
R&D	Research and Development
RPSC	Raytheon Polar Services Company
SAAM	Special Aircraft Airlift Mission
SPoT	South Pole Traverse
SPoT2	South Pole Traverse 2
USAP	U.S. Antarctic Program

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (mass)	0.45359237	kilograms

Executive Summary

The U.S. Antarctic Program (USAP) now operates over-snow traverses to resupply Amundsen-Scott South Pole Station from McMurdo Station, a one-way distance of 1030 miles. During its first three operational seasons (2008–2011), the South Pole Traverse (SPoT) fleet of eight towing tractors delivered an average annual payload of 768,000 lb, most of which was fuel traveling in high-efficiency bladder sleds. These deliveries offset an average of 30 annual LC130 flights to the South Pole that are otherwise needed to deliver the same payload.

We present here an economic analysis of the payback achieved by SPoT during its first three seasons. Costs include SPoT annualized capital and annual operating expenses, and benefits are reduced LC130 costs apportioned per round trip to the South Pole. SPoT's net economic benefits of \$2.0M/year result from significantly lower delivery costs per pound compared with LC130 airlift (\$3.60/lb versus \$6.10/lb, respectively). SPoT's annual net savings in operating costs pay for its capital investment in about 2.3 years for an approximately 43% return on capital investment. Additional benefits of SPoT include reduced air emissions, the ability to transport oversized or overweight cargo, and increased availability of LC130s to support other science operations in Antarctica.

The results here are structured to guide future USAP investments to improve traverse technology and to resupply other remote locations in Antarctica. For example, sled-efficiency improvements dramatically boost benefits: performance gains from using black rather than tan bladders could increase SPoT's annual fuel delivery per roundtrip by 58% and more than double its net economic benefits to \$4.6M/year. Because we apportion LC130 costs per flying hour, it is also straightforward to estimate traverse benefits to resupply other Antarctic locations.

1 Introduction

The National Science Foundation's Division of Polar Programs (NSF-PLR) operates the U.S. Antarctic Program (USAP) through a logistics contractor, most recently Lockheed Martin Antarctic Support Contract (ASC). USAP's mission is to conduct science projects in Antarctica, and for this purpose it maintains three year-round stations and numerous seasonal camps across the continent. McMurdo Station, on Ross Island, is USAP's largest facility, and it serves as the resupply hub for the Amundsen-Scott South Pole Station on the Polar Plateau. Until 2008, essentially all fuel and cargo transported to South Pole was delivered via airlift using ski-equipped LC130 Hercules aircraft. While effective, this airlift is expensive, susceptible to weather delays, and demands a high tempo of operations to achieve up to 380 flights per 120-day summer season at South Pole.

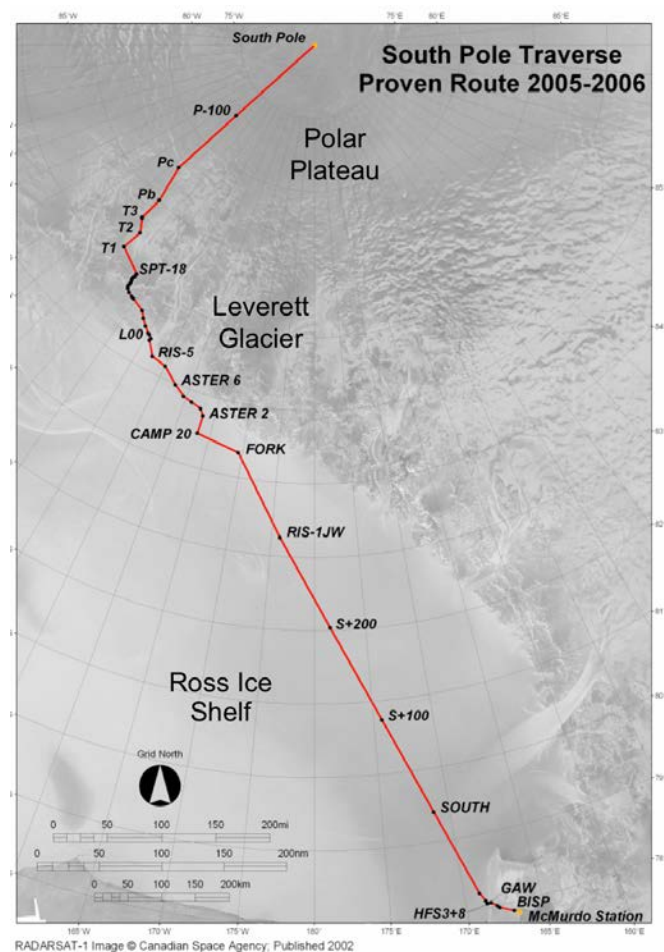
Beginning in 2003, USAP initiated a four-year effort to develop an over-snow, heavy-haul traverse to resupply South Pole Station from McMurdo Station. Four rubber-tracked tractors and one bulldozer pulled trains consisting of steel fuel, cargo, and support sleds directly over unprepared snow. Using ground-penetrating radar, a lighter tracked vehicle surveyed for crevasses in advance of the fleet. This proof-of-concept effort established a 1030-mile safe route across the Ross Ice Shelf, up the Leverett Glacier, and across the Polar Plateau to South Pole (Wright 2006). Figure 1 shows the proven route.

Engineers at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) supported the proof-of-concept effort via numerous safety and mobility studies. Importantly, this USAP-CRREL partnership developed high-efficiency fuel sleds consisting of flexible fuel bladders strapped to flexible sheets of plastic. Compared to the well-performing steel sleds, the bladder sleds are one-sixth the cost, are one-tenth the weight, and triple the fuel delivered per tractor to the South Pole (Lever and Weale 2012).

The South Pole Traverse (SPoT) became an operational department of USAP in 2007, and during the 2008–09 season it conducted the first large-scale, over-snow resupply of South Pole Station. SPoT repeated this success in 2009–10 and 2010–11. During these three seasons, the SPoT

fleet of eight towing tractors delivered an average annual payload of 768,000 lb to South Pole, most of which was fuel towed in bladder sleds. These deliveries offset an average of 30 annual LC130 flights to South Pole. Based in part on this success, USAP expanded its traverse capability to include a second eight-tractor fleet (SPoT2) and two smaller fleets to support science camps in West Antarctica and on the Ross Ice Shelf. NSF-PLR also initiated a traverse in Greenland to resupply from Thule Air Base its science stations on the ice cap (Lever and Weale 2011a, 2011b).

Figure 1. South Pole Traverse proven route, 1030 miles one-way from McMurdo to South Pole.



Blaisdell (2000) and Blaisdell et al. (1997) conducted feasibility analyses, including an economic assessment, to assist NSF-PLR with its decision to initiate the South Pole traverse. We now have sufficient performance and cost data to assess whether SPoT has performed well as in investment in USAP logistics capabilities.

We present here an analysis of the economic payback achieved by SPoT during its first three seasons. Costs include annualized capital and annual operating expenses, and benefits are reduced LC130 airlift costs apportioned per flight offset by SPoT. Our objectives are to quantify the net benefit of SPoT as an investment by USAP, to use these results to estimate benefits for traverse resupply operations elsewhere in Antarctica, and to estimate benefits likely to result from additional improvements in traverse technology.

2 South Pole Traverse Fleet Composition and Deliveries

The 2008–11 SPoT fleet included eight large towing tractors (four Case Quadtracs and four AGCO MT865s) and one lightweight tracked vehicle (a Pisten Bully 100 or a Prinoth BR350) to conduct radar surveys in advance of the fleet. The sled trains consisted of four steel sleds carrying fleet-support modules (living accommodations, electric generators, food, and spare parts) and up to 30 bladder sleds, each carrying two 3000 gal. bladders filled with AN-8 diesel fuel for fleet consumption and for delivery to the South Pole. Figure 2 shows a portion of the SPoT08–09 fleet.

Figure 2. Three SPoT sled trains heading up the Leverett Glacier en route to South Pole during the 2008–09 season. The front-most train includes the living and generator modules (red). Next in line is an MT865 towing a steel fuel sled (grey) and eight 3000 gal. bladders on flexible sleds (tan). The red Quadtrac is towing two coupled sets of bladder sleds, initially consisting of twelve 3000 gal. bladders but subsequently reduced by fleet consumption. The bladder sleds include steel towplates to attach them to spreader bars (red). Note that SPoT08–09 repositioned two steel tanks used as remote fuel caches but did not tow fuel in tanks for delivery to South Pole.



Table 1 provides a summary of SPoT's first three seasons of operational deliveries. We determine the LC130 flights offset based on an average delivered payload of 25,600 lb per flight to South Pole (RPSC 2011). SPoT

also consumed less fuel per pound of payload delivered, averaging 0.56 lb consumed per pound delivered compared with 1.33 lb consumed per pound delivered for LC130 flights to South Pole.

Table 1. Summary of SPoT deliveries to South Pole for its first three operational seasons.

Year	SPoT Fuel Delivered (lb)	SPoT Cargo Delivered (lb)	Total lb delivered	LC130 Flights Offset	LC130 Fuel Burned (gal.)	SPoT Fuel Burned (gal.)	Fuel Saved (gal.)
'08-'09	805,000	129,000	934,000	36.5	178,000	64,000	114,000
'09-'10	662,000	39,400	702,000	27.4	134,000	61,000	72,800
'10-'11	667,000	0	667,000	26.1	127,000	57,200	70,000
Average	712,000	56,000	768,000	30.0	146,000	60,700	85,600

SPoT08–09 delivered the largest payloads for both fuel and cargo during these three first seasons. The high cargo delivery included one of the SPoT towing tractors (51,400 lb) for long-term use at South Pole. But the main reason for the high delivered payload was that we slightly overloaded the SPoT08–09 fleet compared with the carrying capacity (trafficability) of soft snow along the last approximately 150 miles of the route. This situation necessitated daily shuttling of partial sled trains or tandem assist by two tractors on one train, resulting in increased travel time and crew stress. For subsequent years, we reduced gross payload weight, which successfully reduced shuttling over the Polar Plateau and increased average speeds along all sections of the route. This change and the “learning curve” gains from operating experience helped reduce average round trip time from 75 days in 2008–09 to 58 days in 2010–11.

3 South Pole Traverse Costs

Table 2 summarizes the capital and operating costs for SPoT for its first three operational seasons. As a USAP cost center, SPoT's cost are relatively easy to establish. We selected a 2% p.a. (per annum) discount rate to annualize capital costs across the working life of each asset. Brief descriptions of each of the major cost items follow. All costs are in 2011 dollars.

Table 2. Summary of SPoT capital and operating costs.

Capital Costs	Unit Cost	Life	Annualized Unit Cost	Number	Annualized Cost	
Quadtrac (incl. spares)	\$450,000	7	\$69,500	4	\$278,000	
MT865 (incl. spares)	\$540,000	7	\$83,400	4	\$334,000	
Radar vehicle	\$220,000	10	\$24,500	1	\$24,500	
Living-generator module	\$250,000	10	\$27,800	2	\$55,700	
Tool shed/food module	\$110,000	10	\$12,200	2	\$24,500	
Bladder sled (6000 gal. capacity)	\$30,000	3	\$10,400	31	\$322,000	
Spreader	\$20,000	10	\$2,230	15	\$33,400	
misc (e.g., radios, GPS, tents, etc.)	\$200,000	5	\$42,400	1	\$42,400	
CRREL R&D* to initiate	\$1,000,000	20	\$61,200	1	\$61,200	
Total annualized capital costs						\$1,180,000

* Research and development

Operating Costs	Rate (\$/mo)	Months	Persons	Annual Cost	
Management	\$9,480	12	2	\$228,000	
Summer mechanic	\$4,500	6	4	\$108,000	
Winter mechanic	\$2,250	6	2	\$27,000	
Traverse labor	\$7,000	6	6	\$252,000	
Staging labor	\$5,500	2	5	\$55,000	
Maintenance parts				\$100,000	
Materials				\$200,000	
Fuel (\$4.70/gal.)				\$285,000	
Food				\$30,000	
Travel				\$30,000	
Subcontracts & training				\$60,000	
CRREL annual R&D				\$200,000	
Total operating costs					\$1,570,000
SPoT total annual cost					\$2,750,000
SPoT cost/lb delivered					\$3.58

3.1 SPoT capital costs

SPoT's towing tractors are commercial, rubber-tracked, agricultural tractors fitted with optional cold-weather packages. The tractors are variously equipped with snow blades, cranes, and other accessories. Figure 3 shows typical examples of the Quadtracs and MT865 models used. These tractors range from 53,000 to 70,000 lb, depending on accessories, with the Quadtracs all heavier than the MT865s. Nevertheless, both tractors can pull 8–10 full fuel bladders (160,000–200,000 lb of fuel) across most of the SPoT route at speeds ranging from 5 to 8 mph.

Figure 3. Examples of SPoT tractors: Case Quadtrac (upper) and AGCO MT865 (lower).



The capital cost for both tractor types is approximately \$500,000, including spare-parts kits and vessel delivery to McMurdo. Although two Quadtracs carried over from the proof-of-concept phase, we include their

costs here as if they were purchased new for SPoT08–09. Based on a recommended engine overhaul at 3500 hours and 500 hours per year of use, we estimate the working life of the tractors to be seven years. These tractors are likely to have residual value for USAP after this time in locations less demanding than the remote SPoT route. However, we ignore any residual value here.

SPoT used a Pisten Bully 100 during 2008–10 as its radar vehicle to survey for crevasses in advance of the fleet. This vehicle also carried over from the proof-of-concept phase. For 2010–11, SPoT purchased a Prinoth BR350 to serve as its new radar vehicle. The costs of these vehicles are similar (\$220,000), and we include one here with a 10-year life.

Figure 4 shows SPoT's steel fleet-support sleds en route to South Pole in 2008. The living module contained berthing for the crew, a galley, and a communications center. The generator module contained two diesel-electric generators, shower, laundry, snow melting facilities, and an incinerating toilet. A refrigeration module was built into a 20 ft long shipping container, which carried frozen and dry food. A similar sled (called the tool shed) carried fleet spare parts.

Figure 4. Two photos showing SPoT fleet-support sleds. The red living and generator modules are usually towed as a coupled pair. The white module with red borders contains frozen and dry food. A similar sled carries fleet spare parts in a standard shipping container. The small red vehicle in the upper photo is the Pisten Bully 100 used in 2008–09 to conduct radar surveys for crevasse detection in advance of the fleet.



These sleds are heavy relative to their payload carried: the steel undercarriages supporting each module weigh 20,000–25,000 lb. They also develop greater towing resistance per unit weight than bladder sleds. However, they operate reliably and were carried over from the proof-of-concept phase. We include their capital costs here as if they were purchased new for SPoT08–09. The living and generator modules cost about \$250,000 each; the refrigeration module and tool shed cost about \$110,000 each. We estimate their useful lives to be 10 years. We hope eventually to replace their undercarriages with more efficient lightweight sleds.

Figure 5 shows typical bladder-sled trains towed by SPoT. Each sled consists of two 3000 gal. fuel bladders strapped to a sheet of 8 ft wide \times 68 ft long \times 0.5 in. thick high molecular weight polyethylene (HMW-PE). Normally, four sleds (eight bladders) are attached to the same spreader bar (red in Figure 5) to tow as a unit. If desired, a second group of two or four bladders can be towed behind a set of eight via a long towrope connecting the spreader bars. As noted, compared to the well-performing steel sleds, the bladder sleds are one-sixth the cost, are one-tenth the weight, and triple the fuel delivered per tractor to South Pole (Lever and Weale 2012). All fuel delivered to South Pole by SPoT through the three seasons of interest (2008–11) was towed there in bladder sleds.

Figure 5. Bladder sleds towed during SPoT09–10.



The components of bladder sleds are relatively inexpensive: \$10,000 per fuel bladder; \$5000 per HMW-PE sheet; and \$5000 for towplates, strap-

ping, and fittings. These sum to \$15,000 per 3000 gal. transport capacity. By comparison, the proof-of-concept 3000 gal. steel fuel tanks were about \$100,000 each. While efficiency and cost are excellent, SPoT uses the bladders and HMW-PE sheets at lower temperatures and with much more flexing than their normal, stationary service conditions. Consequently, the sleds have experienced a variety of failures (e.g., cracking of HMW-PE sheets when underway, cracks in bladder material when folded for storage), and SPoT has needed to replace 10%–30% of the components each year. We expect to improve the reliability of bladder sleds, via materials designed specifically for traverse purpose, but use here a 3-year life to reflect their service record to date.

The spreader bars used to tow bladder sleds cost about \$20,000 each and should last at least 10 years. We also include miscellaneous gear (e.g., radios, GPS receivers, tools, safety gear) as capital equipment at a total cost of \$200,000 with a 5-year life.

A major cost to initiate SPoT was CRREL's research and development efforts related to crevasse detection and mobility improvements, including full-scale laboratory tests to verify the safety of the new bladder sleds (Lever et al. 2004, 2006, 2010; Weale and Lever 2008). Some of this effort was specific to the proof-of-concept phase (e.g., establishing the McMurdo shear-zone crossing, improving the performance of steel tank and fleet-support sleds), but much of it has enduring value. We estimate the latter component as \$1M and amortize it over 20 years. We also include annual CRREL support to SPoT as \$200,000 per year for ongoing improvements to crevasse-detection and sled technologies.

3.2 SPoT operating costs

Table 2 also lists SPoT annual operating costs. Labor is the single largest expense (43% of the operating costs), followed by fuel (18%), materials (13%), and CRREL R&D support (13%). SPoT requires substantial labor to maintain its tractors and to stage the traverse, including an annual need to inspect bladders and HMW-PE sheets and to reassemble bladder sleds.

Fuel stores in McMurdo provide all fuel for SPoT and LC130 operations to South Pole. USAP's bulk fuel purchase over the past several years has averaged just over \$3 per gal.; tanker-charter and icebreaker costs raise this to about \$4.70 per gal. (Blaisdell and Knuth 2011). This figure does not include off-loading costs, storage, and other costs to maintain the McMur-

do fuel stores. Other SPoT operating costs include maintenance parts, food, travel, and support contracts (Table 2).

3.3 SPoT total delivery costs

For the first three operational seasons, SPoT's annualized capital costs were \$1.18M; and its annual operating costs averaged \$1.57M. Its total annual cost thus averaged about \$2.75M or about \$3.60 per pound of payload delivered to South Pole (768,000 lb 3-year average).

4 LC130 Airlift Costs

USAP has used ski-equipped LC130 Hercules aircraft (Figure 6) to resupply its stations and field camps since the 1960s. Airlift operations from McMurdo provided essentially all of South Pole's fuel and cargo until Year 4 of the proof-of-concept traverse arrived in December 2005. The tempo of airlift operations from 2003 to 2008 was impressive, ranging from 300 to 380 flights per 120-day summer season at South Pole. The pace dropped to an average of 215 flights per season from 2008 to 2011 after completion of the new station and with the onset of SPoT deliveries (RPSC 2011).

Figure 6. LC130 at South Pole about to off-load passengers and cargo.



In general, LC130 costs are established for the entire USAP airlift effort and are not broken down by destination. However, many components of LC130 costs scale with flying hours (e.g., crew labor, fuel consumption, maintenance). Therefore, we will apportion costs to the South Pole airlift based on its fraction of the total LC130 flying hours conducted for USAP.

We analyzed data from the 2010–11 season (RPSC 2011; Blaisdell and Knuth 2011), which had 214 LC130 flights to South Pole and thus should be typical of the 2008–11 period of interest here. Each round trip requires 6.5 hours of flying time. The 214 South Pole resupply flights conducted in 2010–11 thus required 1391 hours or 56% of the total 2506 hours of on-continent LC130 flying hours. By comparison, the next largest fractions of

NSF-PLR also contracts Air New Zealand to provide a facility in Christchurch, New Zealand, to conduct planned depot-level maintenance and unplanned drop-in maintenance. The planned maintenance interval for each LC130 equates to about 70 months, so that 1–2 aircraft receive this maintenance each year. The 109th AW rotates planes from McMurdo to Christchurch for depot-level maintenance and to swap crew. The Air New Zealand contract costs about \$6M per year (NSF 2011) or \$2,400 per on-continent flying hour.

Note that through the MOA, the NSF must pay to repair an LC130 damaged during missions to support NSF (operational or training flights). In addition, NSF must pay to upgrade its own aircraft to satisfy new DOD requirements for LC130s. These aircraft are currently 20–30 years old. At present, we do not have access to historical repair, overhaul, or upgrade costs. We include a modest value of \$50,000 per year for each of the four NSF-owned LC130s but note that these costs could increase substantially as the aircraft continue to age.

The LC130 fleet draws fuel from the McMurdo stores for its on-continent operations. As noted for SPoT operations, this fuel costs about \$4.70/gal. The LC130s burn on average 750 gal. per flying hour, representing about a \$3,500/hr fuel cost.

4.2 LC130 capital costs

Clearly, the LC130 fleet represents a substantial capital investment for DOD and NSF, and some of its annualized capital cost should be apportioned to the South Pole airlift. While NSF is currently the major user of all 10 LC130s, it is possible that DOD will replace its six aircraft when the need arises. Thus, we limit NSF's capital investment to that of four LC130 aircraft. As with previous replacements, we assume a wheeled C130 would be purchased and retrofitted with skis. A new C130J is likely to cost approximately \$70M to \$80M depending on the number ordered (Wikipedia 2012; NDCF 2011). We assume the addition of skis would increase the replacement cost of an LC130 to about \$90M per plane.

Estimating the useful life of the LC130 is difficult. The 109th AW aircraft are 20–30-year-old LC130-H series, which replaced earlier LC-130Ds after 25 years of service (Firebirds 2012; NYANG 2012). The NSF-owned aircraft are older airframes, transferred from the Navy's VXE-6 squadron, but were upgraded to LC130-H in the early 2000s. It is possible that these

aircraft could be maintained, overhauled, and upgraded indefinitely, but this seems unlikely. Rather, we use 50 years as the life for these assets and note that repair and upgrade costs will probably escalate from historical levels. We again use a 2% p.a. discount rate.

Note that the LC130 fleet also provides airlift support for the Arctic program of NSF-PLR with flights from the 109th AW base at Scotia, NY, to Kangerlussuaq and Thule, Greenland, and between these airfields and Summit Station and other camps on the ice cap (Lever and Weale 2011a, 2011b). This Arctic airlift averages about 500 flying hours per year. That is, the LC130 fleet flies about 3000 hours per year on behalf of NSF-PLR. The annualized capital cost of the four NSF-owned LC130s thus converts to \$3,810 per flying hour.

4.3 Other airlift costs

USAP annually prepares and maintains airfields at McMurdo and South Pole and staffs operations at both locations to conduct airlift operations. These are substantial undertakings in terms of equipment and personnel involved. McMurdo airfield supports USAP intercontinental and on-continent flights for all aircraft types. It would be reasonable to apportion McMurdo costs to the South Pole airlift based on its fraction of total flights. Nearly all airfield costs at South Pole are incurred to support the LC130 airlift (minor passenger flights by Bassler and Twin Otter aircraft notwithstanding). Identifying and apportioning these airfield costs would require substantial effort. We omit them here but note that this tends to underestimate total South Pole airlift costs.

4.4 LC130 total delivery costs

Table 3 summarizes the cost components for the LC130 South Pole airlift per hour and per flight. The 109th AW annual contract is the largest component (59%), followed by annualized capital costs (16%), fuel (15%), and depot-level maintenance (10%). The costs sum to \$157,000 per South Pole flight or \$24,200/hr of flying time. This equates to \$6.10/lb delivered based on the 2010–11 average delivered payload of 25,600 lb per flight.

We may crosscheck these costs with those determined for the LC130 airlift in Greenland (Lever and Weale 2011b). In 2009, NSF-PLR paid \$6,816/hr of LC130 flying time, the so-called SAAM or Special Aircraft Airlift Mission

rate. This figure includes fuel and a 10% discount for early scheduling. The SAAM rate increased to \$8,017/hr in 2012. In addition, NSF-PLR must pay to position the aircraft in Greenland, which has averaged 75% of in-Greenland flight-hour costs. Thus, the average LC130 airlift cost during 2009–11 was \$12,000–\$14,000 per in-Greenland flying hour, including fuel. This range is close to the figure determined here for the South Pole airlift: \$17,900/hr including fuel and positioning costs (the latter included in 109th AW annual contract). The higher figure for the South Pole airlift likely results from higher 109th AW costs to position planes in Antarctic and to station crew in McMurdo rather than in their home base in Scotia, NY.

While \$6.10/lb for the South Pole airlift might seem expensive, it is similar to commercial costs to fly goods from the U.S. to Thule Air Base in Greenland. For example, the U.S. Air Force Air Mobility Command (AMC) contracts weekly flights to Thule from Baltimore, MD. In 2011, CRREL shipped approximately 200 lb of equipment on these flights at a cost of \$7.10/lb. While the distance is greater than McMurdo to South Pole, these AMC flights also carry paying passengers to offset costs.

5 Economic Benefits of the South Pole Traverse

5.1 Average economic benefits

During its first three operations seasons, 2008–11, SPoT averaged 768,000 lb of payload delivered annually to South Pole (Table 1). These deliveries offset 30 annual LC130 flights to South Pole, based on an average payload of 25,600 lb/flight. SPoT's annual cost to achieve this performance was \$2.75M (total operating and annualized capital cost, Table 2). Conversely, the annualized capital and operating costs of LC130 airlifts to deliver the same payload sums to \$4.72M. That is, the net benefit of SPoT to USAP was approximately \$2.0M/year or \$5.9M over its first three seasons of operation.

SPoT08–11 operating costs averaged \$1.57M/year. SPoT thus achieved a net operational savings to USAP of \$3.14M/year compared with LC130 airlifts, sufficient to pay all its capital costs (\$7.33M) in 2.3 years of operation. This is an excellent return on capital investment (43%).

Note that SPoT achieves net benefits regardless of how USAP consumes these benefits. USAP could reduce its total LC130 airlift costs (i.e., save money on logistics) or it could reprogram the offset flights to support deep-field science in Antarctica (i.e., expand its science capabilities). The net benefits derive from USAP's investment in SPoT as an alternative to LC130 resupply of South Pole.

5.2 Incremental benefits from efficiency gains

Since the proof-of-concept phase, CRREL has worked with SPoT to increase sled efficiency (payload carried per unit towing force required). Lever and Weale (2012) summarize these gains for bladder sleds: they essentially triple the fuel delivered to South Pole per towing tractor compared with steel tank sleds. Collaboration with NSF-PLR's Greenland Inland Traverse (GrIT) shows potential to achieve similar gains for cargo sleds (Lever et al. 2012). In both cases, lightweight high-efficiency sleds perform better and cost less than their steel counterparts. They increase the per-tractor payload delivered to South Pole for essentially the same operating costs (fuel consumption, labor, maintenance, etc.).

We have included ongoing \$200,000/year R&D costs for SPoT to seek additional efficiency gains. The recently documented dependence of sled towing resistance on sled–snow interface temperature provides a good example (Lever 2011; Lever and Weale 2012). Warmer sleds tow easier than colder ones, and passive solar gain on black bladders produces significant performance gains. That is, simply replacing worn-out tan bladders with black ones will increase SPoT’s per-tractor fuel delivery capacity. This has a dramatic effect on the net benefits achieved.

The 2008–11 average outbound towing capacity of SPoT equated to 57 fuel bladders (1.2M lb of fuel) plus the four fleet-support sleds. The towing capacity of 1.5 tractors was needed to tow the fleet-support sleds. The remaining fleet capacity averaged about 9 fuel bladders per tractor (sled trains of 8–10 bladders). Field tests near McMurdo indicated that black bladders could boost per-tractor capacity to 12–16 bladders (Lever and Weale 2012). The second SPoT fleet achieved this performance across a portion of the Ross Ice Shelf during the 2011–12 season. Even without improving the fleet-support sleds, 12 bladders per tractor represents a potential delivery increase of 64,000 gal. per year or 58% more than the 2008–11 average. The effect on net annual benefits is even more impressive: it more than doubles, from \$2.0M/year to \$4.6M/year (an additional 17.4 LC130 flights offset). Because the SPoT fleet already covers its costs, efficiency gains dramatically boost benefits.

5.3 Other SPoT economic benefits

SPoT can achieve significant benefits beyond reductions in cost per pound of payload delivered. The most straightforward examples result from transport of items that are too large or too heavy for a single LC130 flight. SPoT can tow (or drive) intact tractors, bulldozers, and other heavy equipment needed at South Pole. It should also be able to tow prefabricated buildings and large science equipment on efficient, lightweight cargo sleds (Lever et al. 2012). LC130 airlift requires labor to disassemble the equipment in McMurdo (or at the U.S. originating supplier) and labor and facilities to reassemble it at South Pole, plus the cost per pound for multiple LC130 flights. These benefits can be quantified for specific cargo; additional benefits derive from the convenience and quality assurance that results by transporting large equipment intact from the U.S. through to South Pole.

6 Air Emissions Benefits

Lever and Weale (2011b) estimated reductions in air emissions for the proposed GrIT compared with LC130 airlift to resupply Summit Station. They based their analysis on the Comprehensive Environmental Evaluation (CEE) prepared by NSF to assess potential environmental impacts of Antarctic traverses (NSF 2004). We repeat the key points here and apply the method to estimate the air emissions benefits of SPoT.

NSF-PLR prepared a CEE to identify and to evaluate potential environmental and operational impacts of surface traverses in Antarctica, partly to support SPoT's proof of concept. The CEE was subject to the scrutiny of and approval by other member countries covered by the Antarctic Treaty.

Section 6.3.2 of the CEE presented estimates of cargo weights, fuel usage, and air emissions for SPoT scenarios and LC130 resupply flights. It used models developed by the U.S. Environmental Protection Agency (EPA) to estimate annual emission for air pollutants from hydrocarbon fuel combustion and included emissions from traverse tractors, generators, heaters, and snowmobiles and LC130 engines. Table 6-3 of the CEE summarized these results.

We now know the actual performance of SPoT for 2008–11 in terms of payload delivered and fuel consumed. The CEE's traverse scenarios, equipment anticipated, distances traveled, and LC130 flight profiles are sufficiently similar that we may use normalized predicted emissions (lb/1000 lb fuel consumption) to estimate actual emissions. Table 4 presents the results for all five combustion byproducts analyzed in the CEE.

SPoT offers impressive reductions in all air emissions compared with LC130 flights. The main reductions result from much lower emissions per unit fuel consumed (about two orders-of-magnitude). Secondary reductions derive from lower fuel consumption to deliver the same payload to South Pole (about a 60% reduction). For simplicity, we also present the average reduction for all five pollutants, ignoring differences in environmental impacts from these pollutants. By this simple measure, SPoT's emissions of five key air pollutants average less than 1% of those from the LC130 airlift.

Table 4. Annual air emissions for SPoT08–11 compared with those by LC130 airlift. The first three rows derive from Table 6-3 of the CEE for South Pole resupply (NSF 2004), normalized by fuel consumed. The last row presents the SPoT/LC130 emission ratios to resupply South Pole.

Delivery Mode	Fuel Consumed (1000 lb)	Normalized Emissions (lb/1000 lb fuel consumption)					Average Emission Ratio
		Sulfur Oxides	Nitrogen Oxides	Carbon Monoxide	Exhaust Hydrocarbons	Particulates	
SPoT (CEE)	1387	0.079	0.043	0.016	0.002	0.003	
LC130 (CEE)	2220	1.35	10.66	7.16	3.19	2.93	
SPoT/LC130 emission ratio per unit fuel use (CEE)		5.9%	0.40%	0.22%	0.07%	0.12%	1.3%
SPoT/LC130 average fuel use 2008–11	0.422						
SPoT/LC130 emission ratio per unit payload delivered to South Pole 2008–11		2.5%	0.17%	0.09%	0.03%	0.05%	0.56%

Since the date of the CEE, carbon-dioxide emissions have become an important environmental concern. They scale primarily with quantity of fuel burned, so the CO₂ emission of SPoT is 42% that of the LC130 airlift, less impressive but still significant.

Note that this analysis ignores differences in the location of the air emissions between SPoT and LC130 resupply profiles. All emissions by SPoT are at ground level while most of the LC130 emissions occur at their flight altitude. These location differences also imply different environmental impacts. By design, both SPoT and LC130 resupply missions approach South Pole away from the clean-air and quiet sectors to minimize impacts on science activities.

7 Estimating Benefits for Other Traverse Missions

We have apportioned LC130 operating and capital costs according to on-continent flying hours (\$24,200/hr total) and have calculated SPoT flight offsets based on the average payload delivered per flight to South Pole (25,600 lb). We may generalize this calculation for any Antarctic destination by determining the round trip flying time and ACL for that location. However, additional airlift costs occur for remote destinations (i.e., those without existing skiways and infrastructure). These include low ACL flights to establish a camp, skiway preparation and camp costs, field-crew labor, etc.

We may estimate traverse costs for other missions based on round trip transit time and SPoT labor rates, fuel consumption, maintenance, and annualized capital costs per hour. Traverses tow their own accommodations and food and can arrive with considerable labor capacity to install, resupply, or remove remote camps. Thus, traverse transit and on-site costs are easy to estimate. Less well known is the per-tractor payload capacity across unknown snow conditions to new, remote sites. Soft snow across the Polar Plateau can dramatically reduce payload capacity, and uncertainty in snow conditions unfortunately demands planning for conservatively low payloads.

While beyond the present scope, it would be worthwhile to compare costs for specific traverse missions with LC130 airlift costs for those same missions. The resulting difference (net benefits) could then be compared with the benefits lost by diverting SPoT assets to perform the missions or the extra costs to acquire additional traverse equipment and personnel.

8 Discussion

The analysis here shows that SPoT saved USAP approximately \$5.9M over its first three seasons of operation by offsetting LC130 flights to South Pole. This figure accounts for the annualized capital and annual operating costs of both resupply modes.

We have good documentation of costs and payload delivered by SPoT because it is essentially an independent USAP work center. Several factors quantifying the LC130 South Pole airlift are also well known: the average payload, fuel consumption, and flight hours; the total USAP LC130 airlift hours; the 109th AW annual contract; the depot-level maintenance contract; and McMurdo fuel cost (also applied to SPoT). Less well known are historical LC130 repair, overhaul, and upgrade costs and how they trend as the planes age. The estimate used here (\$50,000 per plane per year) is low relative to other cost components. It seems likely that repair, overhaul, and upgrade costs will increase substantially as the planes age. Follow-on research should yield a better estimate of these costs.

The annualized capital cost of the LC130 fleet is also somewhat uncertain. The purchase price assumed here (\$90M per plane) uses recent C130J prices boosted to allow for ski retrofit. The working life of an LC130 is also an estimate. The planes are now 20–30 years old. We have used 50 years, a long life, which tends to minimize LC130 annualized capital cost. The choice of a 2% p.a. discount rate to annualize capital costs reflects current government bond rates. A higher value would increase LC130 total annual costs. Importantly, we have assumed that DOD will replace its six aircraft when the need arises. However, NSF-PLR is currently the major user of LC130 airlift capacity; it is potentially exposed to replacement costs for all the aircraft it needs, including those owned by DOD.

In principle, we could assess the incremental economic benefits and incremental costs to USAP of investing in SPoT. Essentially all SPoT costs are incremental as this is a new capability to USAP. Incremental benefits would be the incremental reductions in LC130 airlift costs for 30 annual South Pole flights offset. These benefits would be the same as determined here provided all LC130 costs scale with flying hours.

LC130 fuel, maintenance, and crew costs scale primarily with flying hours, as should repair, overhaul, and upgrade costs and the reduction in useful life. Nevertheless, some LC130 costs are probably fixed costs, say some fractions of the 109th AW annual contract and the Air New Zealand maintenance contract. The best way to determine the fixed-cost fractions would be to have these contracts explicitly identify fixed and variable costs. Absent this information, we have used the simpler approach of scaling all LC130 costs with flying hours. This approach tends to overstate the economic benefits of SPoT.

We have omitted airfield infrastructure from LC130 costs, and this tends to counterbalance the aforementioned simplification. Some airfield costs are fixed to support any level of USAP airlift operations. However, the South Pole airlift represents the majority (56%) of all LC130 on-continent flights and must incrementally increase McMurdo airfield costs via fuel and cargo handling, firefighting, maintenance, tower, and transportation costs. Essentially all airfield costs at South Pole should be applied to the LC130 airlift, and a substantial proportion would scale with the number of flights. Neglecting these costs tends to understate the economic benefits of SPoT.

The McMurdo food and lodging costs for the 109th aircrew also scale primarily with crew size and hence with flying hours. SPoT incurs similar costs during staging and winter maintenance, but it pays for (and tows) its in-field food and lodging. We neglect these costs for both modes as they partially cancel each other. The same is true for USAP-provided airfares to and from New Zealand: they are small and partially cancel for both modes.

SPoT efficiency gains from CRREL R&D have already yielded big benefits: fuel bladder sleds tripled the fuel delivery possible per SPoT tractor compared with proof-of-concept steel tank sleds. Annual R&D investment, included in SPoT operating costs as \$200,000/year, offers the potential for similarly impressive payback. Solar gain via black bladders can boost the per-tractor capacity to 12 bladders from the 2008–11 average of roughly 9 bladders. This would more than double the net economic benefit per SPoT round trip, from \$2.0M/year to \$4.6M/year, and represent a return on the annual R&D investment of a whopping 1300%. Lightweight, high-efficiency cargo sleds, jointly developed with GrIT, offer the potential to tow prefabricated buildings and science equipment intact to South Pole.

Besides lower delivery costs per pound, SPoT delivery would save additional costs for disassembly and reassembly otherwise needed for airlift delivery.

Robotic leader-follower technology could offer additional efficiency gains. At present, the SPoT crews work 12 hours per day with 10 hours of driving and 2 hours for startup, lunch, cleanup, and refueling. Four robotic follower tractors per fleet would enable the same crews to operate in two shifts, doubling normal daily advance while retaining the option to operate all tractors manually if needed. The round trip travel times would thus drop from approximately 45 days to 25–30 days, providing a sufficient margin to enable each SPoT fleet to conduct two round trips per season. The method outlined here provides a means to estimate the net economic benefits, and hence payback, of an investment in robotic tractors.

Air emission benefits by SPoT delivery compared with LC130 airlift, while not monetary, are nonetheless important. Reductions in five types of air pollutants average two orders of magnitude, owing to lower tractor emissions per pound of fuel burned. Lower fuel burned per pound of cargo delivered (42%) increases this benefit and produces proportional reductions in CO₂ emissions.

9 Summary and Conclusions

USAP now operates over-snow traverses to resupply Amundsen-Scott South Pole Station from McMurdo Station, a one-way distance of 1030 miles. During its first three operational seasons (2008–11), the SPoT fleet of eight towing tractors delivered an average annual payload of 768,000 lb, most of which was fuel towed in high-efficiency bladder sleds. These deliveries offset an average of 30 annual LC130 flights to South Pole otherwise needed to deliver the same payload.

We developed an economic analysis of the payback achieved by SPoT during its first three seasons. Costs include SPoT annualized capital and annual operating costs, and benefits are reduced LC130 costs apportioned per round trip to South Pole. SPoT's net economic benefits of \$2.0M/year result from significantly lower delivery costs per pound compared with corresponding LC130 costs (\$3.60/lb versus \$6.10/lb, respectively). SPoT's annual net savings in operating costs pays for its capital investment in about 2.3 years for an approximately 43% return on capital investment. Additional benefits of SPoT include significantly reduced air emissions, the ability to transport outsized or overweight cargo, and the increased availability of LC130s to support other science operations in remote sectors of Antarctica.

The results here were structured to help guide USAP investments to improve traverse technology and to resupply other remote locations in Antarctica by this method. For example, sled-efficiency improvements dramatically boost benefits: performance gains from using black rather than tan bladders could increase SPoT's annual fuel delivery per round trip by 58% and more than double its net economic benefits to \$4.6M/year. Because we apportion LC130 costs per flying hour, it is also straightforward to estimate traverse benefits to resupply other Antarctic locations.

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REPORT DOCUMENTATION PAGE

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1. REPORT DATE (DD-MM-YYYY) 29-05-2014		2. REPORT TYPE Technical Report/Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Economic Analysis of the South Pole Traverse				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) James H. Lever and Paul Thur				5d. PROJECT NUMBER	
				5e. TASK NUMBER EP-ANT-12-05	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Cold Regions Research and Engineering Laboratory (CRREL) U.S. Army Engineer Research and Development Center 72 Lyme Road Hanover, NH 03755-1290				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CRREL TR-14-7	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Science Foundation, Division of Polar Programs, Antarctic Infrastructure and Logistics Arlington, VA 22230				10. SPONSOR/MONITOR'S ACRONYM(S) NSF	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES Engineering for Polar Operations, Logistics, and Research (EPOLAR)					
14. ABSTRACT <p>The U.S. Antarctic Program (USAP) operates the South Pole Traverse (SPoT) to resupply Amundsen-Scott South Pole Station from McMurdo Station. During its first three operational seasons (2008–2011), SPoT's eight tractors delivered an average annual payload of 768,000 lb, most of which was fuel traveling in high-efficiency bladder sleds. These deliveries offset an average of 30 annual LC130 flights to South Pole.</p> <p>We present here an economic analysis of the payback achieved by SPoT during its first three seasons. Costs include SPoT annualized capital and annual operating expenses, and benefits are reduced LC130 costs apportioned per round-trip to South Pole. SPoT's net economic benefits of \$2.0M/year result from significantly lower delivery costs per pound compared with LC130 airlift (\$3.60/lb versus \$6.10/lb, respectively). Additional benefits of SPoT include reduced air emissions, ability to transport oversized or overweight cargo, and increased availability of LC130s to support other science operations in Antarctica.</p> <p>The results here are structured to guide future USAP investments. For example, sled-efficiency improvements dramatically boost benefits: performance gains from using black rather than tan bladders could increase SPoT's annual fuel delivery per round trip by 58% and more than double its net economic benefits to \$4.6M/year.</p>					
15. SUBJECT TERMS Antarctica Efficiency		EPOLAR NSF Over-snow resupply		Polar logistics Return on investment South Pole Traverse	
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			None