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Advances in Antarctic Sled Technology

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Abstract

This report discusses the recent advances in the performance of sleds developed for polar resupply traverses. Researchers at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) have guided developments by using field mobility measurements that routinely included sled-train towing force, speed, and air temperature. Owing to its dominant contribution to towing resistance, researchers have made special efforts to understand the processes and design choices that affect sled–snow sliding friction. As a result, polar traverses now tow lightweight, flexible sleds that achieve significant performance and cost advantages relative to steel sleds. With an emphasis on Antarctic traverses, this report summarizes sled developments, performance data, insights, and future goals for sled technology.

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Preface

This study was conducted for National Science Foundation, Division of Polar Programs (NSF-PLR) under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-12-05, EP-ANT-13-05, and EP-ANT-14-05, “Mobility Support for the South Pole Traverse.” The technical monitors were George Blaisdell, Chief Program Manager, and Margaret Knuth, Operations Manager, NSF-PLR, Antarctic Infrastructure and Logistics.

The work was performed Dr. James H. Lever, Jason C. Weale, and Monica J. Preston (Force Projection and Sustainment Branch, Dr. Toyoki Nogami, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), and Dr. Thomas U. Kaempfer, AF-Consult Switzerland Ltd. At the time of publication, Janet Hardy was the program manager for EPOLAR. Dr. Loren Wehmeyer was Chief of the Research and Engineering Division of ERDC-CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

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COL Bryan S. Greene was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

AGAP	Antarctic Gamburtsev Province
ARCS	Air-Ride Cargo Sled(s)
ATL	Aero Tec Laboratories
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics, and Research
ERDC	Engineer Research and Development Center
FFF	Federal Fabrics-Fibers
GPR	Ground-Penetrating Radar
GPS	Global Positioning System
GrIT	Greenland Inland Traverse
HMW-PE	High Molecular Weight Polyethylene
ISO	International Standards Organization
NSF	National Science Foundation
PIG	Pine Island Glacier
PLR	Division of Polar Programs
RIS	Ross Ice Shelf
SPoT	South Pole Traverse
USAP	U.S. Antarctic Program
WISSARD	Whillans Ice Stream Subglacial Access Research Drilling

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
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 (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms

Executive Summary

The National Science Foundation's Division of Polar Programs (NSF-PLR) operates over-snow traverses to resupply its research stations in Antarctic and Greenland. From their onsets, engineers at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) have helped these traverses develop high-efficiency sleds to increase their economic paybacks. Mobility measurements have routinely included towing force, speed, and air temperature, and we have made dedicated efforts to understand the role of sled–snow sliding friction. With an emphasis on Antarctic traverses, this report summarizes sled developments, performance data, insights, and future goals for sled technology.

Fuel Sleds

Starting from McMurdo Station, the South Pole Traverse (SPoT) crosses 1030 miles of snow to resupply South Pole Station. From 2002 to 2006, SPoT towed its fuel in steel sleds while establishing a safe route (Figure ES1). By 2008, CRREL and SPoT had collaboratively developed and deployed lightweight, flexible fuel-bladder sleds, and deliverable payload per tractor tripled from 6000 gal. to 18,000 gal. (Lever and Weale 2012). These sleds consist of fuel bladders strapped to sheets of high molecular weight polyethylene (HMW-PE). Compared with steel fuel sleds, they have a much higher payload fraction (0.95 vs. 0.63) and negligible snow-compaction resistance owing to their lower, more uniform ground pressure (0.91 psi vs. 2.4 psi).

Figure ES1. SPoT04-05 steel fuel sleds (*left*) and SPoT09-10 bladder sleds (*right*). The tanks and bladders each hold 3000 gal. of fuel, and the images show a full outbound load for a SPoT towing tractor. Accounting for the approximately 6000 gal. each tractor consumes per round trip, bladder sleds triple the SPoT fuel delivery to South Pole from 6000 gal. to 18,000 gal. per tractor.

Sled–snow sliding friction dominates the towing resistance of bladder sleds. Field mobility tests in 2009 revealed that frictional heating warms the sled–snow interface, and the transient decrease in towing resistance correlates with increasing interface temperature. Friction theory explains this behavior (Colbeck 1988, 1992; Lehtovaara 1989). Cold, dry snow causes high start-up resistance, but as the sled moves, frictional heating increases the interface temperature and partially melts contacting snow grains. The resulting meltwater layer lubricates the sled–snow interface, and resistance drops. The thermal budget of the sled–snow system thus plays a critical role in sliding friction and hence sled towing resistance.

Kaempfer and Lever (2009) developed a simple model to simulate the sliding friction of bladder sleds. It tracked the sled–snow thermal fluxes and interface meltwater production as functions of time and position along the sled to calculate local friction and overall towing resistance. Despite its lack of tuning parameters, it yielded good agreement with the duration of start-up transients and steady-state resistance measured for SPoT bladder sleds.

The modeling revealed the importance of sled length. Longer sleds generate more frictional heating, higher temperatures under the rear bladder, and thus lower resistance per unit weight. Although SPoT has always towed two bladders in line on each sheet of HMW-PE, the Greenland Inland Traverse (GrIT) switched from single- to dual-bladder sleds based on these findings.

Model results also highlighted an important positive feedback: higher towing speeds increase frictional heating, which increases meltwater production and decreases towing resistance, thereby allowing higher towing speeds. To capitalize on this effect, we recommended that SPoT and GrIT tractor operators attempt to pull at maximum engine power at all times after initial start-up, shifting upwards as resistance drops. The tractor operators have generally adopted this recommendation. It reduces the duration of start-up transients and contributes to lower trip times.

The simulations also revealed that smaller sled–snow contact area produced higher temperatures, more rapid meltwater development, and thus lower resistance. Because the initial contact area can be less than 1% of the sled area, flash heating and melting probably occurs along the sled at the onset of motion and near the front of the sled at all times. Our measurements support this explanation: a steep temperature rise at the front of the first bladder, an abrupt drop in temperature resulting from flash melting and lubrication, a more gradual rise along the length of the bladder, and a repeat of this pattern under the second bladder but at higher temperatures.

Importantly, although bladder sleds produce negligible snow-compaction resistance, snow strength could play a role in sliding friction via contact area. Softer snow requires more snow-grain contact to support the sled weight, which spreads the frictional heating across more contact area. Thus, frictional heating benefits are probably lower in regions of soft snow, such as in the Plateau Swamp section of SPoT's route. Through a basic-research project (Lever et al. 2014a), we hope to quantify the evolution of microscale contact area and the role of snow strength on sliding friction so that we can more accurately model macro-scale systems such as fuel-bladder sleds.

Armed with these insights into sliding friction, we recommended that SPoT eventually replace its tan bladders with black ones (Figure ES2). Black bladders capitalize on solar gain to warm the sled–snow interface, and SPoT began to deploy them in 2010. During towing tests of eight-bladder sled trains, fuel was 4.1°C higher in the black bladders (11°C higher than the air temperature), and towing resistance per unit weight (T/W) dropped by approximately one-third compared with the tan bladders. Payload efficiency, or payload weight per unit towing force (W_p/T), thus jumped 53%, indicating that for the same towing effort, a tractor could tow 12 black bladders rather than 8 tan ones.

Figure ES2. A set of eight black bladders on SPoT10-11. To investigate sliding friction, the left-most sled was instrumented to measure the sled–snow interface, fuel and air temperatures, and solar irradiance.

We have compiled the field mobility data from SPoT10-11, SPoT11-12, and SPoT12-13. The benefits of black bladders over tan ones are most pronounced on the Polar Plateau where cold, soft snow poses the most demanding mobility conditions. For the coldest air-temperature interval, −28 ± 5°C, W_p/T was 6.8 for tan bladders and 11.6 for black bladders. That is, for no cost penalty, black bladders produced a 70% efficiency gain over tan ones across the most demanding section of SPoT's route. This benefit derived directly from investigations into sled–snow sliding friction and the choice to use passive solar gain to warm the sled–snow interface.

The few data we have for steel fuel sleds at −28 ± 5°C in Antarctica and Greenland (Lever and Weale 2011) suggest T/W is about 0.5 for that temperature interval. Accounting for the payload fraction (0.63), we estimate W_p/T is about 1.3 for steel fuel sleds at −28 ± 5°C. That is, black-bladder sleds have achieved a performance gain of about 10:1 under the most demanding conditions compared with the steel sleds they have replaced. Furthermore, bladder sleds are less expensive, currently costing $16,000 versus $102,000 (2007) per 3000 gal. capacity.

Black-bladder sleds are now a proven, high-performance technology, and we anticipate no design changes for the near future. However, the data here suggest that the first outbound fleet each season, SPoT1, could depart McMurdo with 10–12 bladders per tractor rather than 8 and still achieve reliable mobility performance and low round-trip times. Similarly the second outbound fleet, SPoT2, traveling over SPoT1's compacted trail, could reliably boost its per-tractor bladder count to 12–16 across the Ross Ice Shelf, which would open options to shuttle bladders from the base of the Leverett Glacier to South Pole as a means to increase throughput, and hence payback, of the two fleets. Increasing the outbound per-tractor load to 12 bladders would more than double the net economic payback of a SPoT round trip to $4.6M (Lever and Thur 2014).

Cargo Sleds

SPoT's fleet-support sleds are cargo sleds that carry food, power, spare-parts, and living-quarters modules on steel ski kits consisting of steerable, cable-connected front and rear ski assemblies. Designed to carry International Standards Organization (ISO) shipping containers, these sleds exhibit similarly poor towing performance as steel fuel sleds. Furthermore, GrIT delivers proportionally more cargo than fuel, and significant cost savings are possible for NSF-PLR if large facilities (science or infrastructure) can be prefabricated in the U.S. and transported intact to their respective research stations. For these reasons, CRREL, SPoT, and GrIT have collaborated to develop lightweight cargo sleds that seek the payload efficiency of fuel-bladder sleds.

Our approach has used air-filled pontoons as compliant, lightweight suspensions between wood-framed decks and HMW-PE sheets. Design targets for these Air-Ride Cargo Sleds (ARCS) were 5000 lb tare weight, 20,000 lb payload capacity (payload fraction of $W_p/W = 0.80$), and 1 psi ground pressure. Conceptually, the flat deck could accommodate a range of payloads, including ISO containers, prefabricated modules, and loose-loaded cargo. The air-ride suspension would cushion the payload over rough sastrugi.

SPoT10-11 deployed the first prototype ARCS, designed to carry its refrigerated food module (Figure ES3). Compared with the steel sled it replaced, the ARCS tare weight dropped from 19,500 lb to 12,500 lb, and pre-departure mobility tests showed that resistance per unit weight dropped by 60%. Consequently, payload efficiency more than doubled to $W_p/T = 5.6$. Unfortunately, the off-the-shelf pontoons failed during the first few days of travel, so SPoT crew swapped the food module back onto its ISO kit to complete the round trip.

Figure ES3. SPoT10-11's refrigerated food module on a steel-ski ISO kit (*left*) and on prototype ARCS (*right*).

GrIT11 had more time to procure two revised ARCS that included custom-made pontoons and higher strength–weight ratio decks. Tare weight dropped to 5000 lb, and pre-departure tests with 23,000 lb of payload yielded a payload efficiency of $W_p/T \approx 6$. Importantly, both ARCS completed the 1460-mile Thule–Summit round trip with no pontoon failures although high air-leakage rates and snow intrusion between the pontoons demanded another round of design revisions.

For 2011–12, we designed "tube-in-pouch" ARCS for SPoT, GrIT, and the Pine Island Glacier (PIG) traverse. These sleds used fabric pouches bolted between the HMW-PE sheets and the cargo decks to form the structural connections, to prevent snow intrusion, and to hold cylindrical pontoons in individual pouch sleeves. Based on cyclic compression tests at −40°C (Weale et al. 2011), we selected pontoons that used a two-layer fabric construction derived from rapidly deployable shelters.

PIG11-12 deployed four 10,000 lb capacity ARCS, and we conducted pre-departure mobility tests on one of them (Figure ES4). Loaded with 8000 lb of payload, the sled showed excellent stability and a smooth ride over 3–4 ft high snow bumps at 2–4 mph, and the pouch prevented snow intrusion during turns. Measured payload efficiency was $W_P/T \approx 8$ at −11.5°C. The PIG11-12 ARCS completed approximately 1700 miles of travel, much of it over soft snow and large sastrugi. They rode well and had no problems with snow intrusion, air leakage, or pouch material failure. PIG12-13 used the same ARCS with similarly successful results.

Figure ES4. Tube-in-pouch ARCS deployed on PIG11-12 (*left*) and GrIT12 (*right*). These ARCS completed thousands of miles of polar travel with only minor durability issues.

GrIT12 deployed five larger ARCS based on the same tube-in-pouch design (Figure ES4). Payload fraction was 0.83, and, using these ARCS, GrIT successfully delivered two 24,000 lb fuel-storage tanks and a 14,000 lb roller packer to Summit Station. The crew reported good stability and ride quality and no pontoon leaks. They corrected minor tearing of the pouch by installing diagonal straps at the pouch corners, a precaution relayed to SPoT. GrIT12 also deployed a 7000 lb prefabricated science module on a smaller ARCS. It too performed well, confirming the utility of ARCS to support light science traverses.

SPoT put its ARCS into service during 2012–13 to carry a tool shed and miscellaneous cargo. These ARCS also performed very reliably with no air leakage and no tearing of fabric pouches. Minor cracks formed on some pouches, resulting from flexing at low temperatures. For 2014–15, SPoT acquired ARCS pouches constructed from more durable fabric, selected based on −40°C flex tests (Lever et al. 2014b). These ARCS performed well and remain in service.

Concurrently with ARCS development, CRREL helped redesign the ISO kits to transport scientific facilities and a drilling rig for the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project. These "ISO-2" kits aimed to reduce towing resistance, increase payload fraction, and reduce fabrication costs. Changes included larger, lighter flat-bottomed skis with elliptical noses, non-steering ski assemblies connected via the ISO container, and cables rather than hard-hitches. Tare weight dropped by 5500 lb, and ground pressure decreased from 2.5 psi to 1.9 psi.

SPoT towed several ISO-2 sleds across the Ross Ice Shelf in 2012–13. Sleds with unmodified ISO containers performed well. Unfortunately, several WISSARD containers were modified for use as laboratories and living spaces and thus had numerous cutouts for windows and doors. These containers broke welds and cracked their steel skins in ways consistent with high shear stresses resulting from torsional loads. We have since passed along load specifications for modified ISO containers intended for ISO-2 kits. Note that the original ISO kits reduced torsion-generated stresses by unintentionally accommodating roll motion in their turntable pins, which led to numerous bent and failed pins and many difficult field repairs.

Unfortunately, we cannot easily compare the performance of steel and lightweight cargo sleds. We have no resistance data for ARCS across the Polar Plateau. The few data for ISO kits at −28 ± 5°C suggest that $R/W \approx 0.4$ and $T/W \approx 0.5$ are reasonable averages, and the payload fraction for a typical 20,000 lb container is $W_p/W = 0.51$. Thus, we may estimate the payload efficiency of the ISO kits as $W_p/T \approx 1.0$ at −28 ± 5°C, slightly worse than steel fuel sleds.

ISO-2 kits should improve payload efficiency compared with ISO kits via higher payload fraction (0.59) and lower resistance per unit weight, resulting from lower ground pressure. The limited WISSARD data are encouraging but inconclusive owing to higher air temperatures and mixed sled trains. Nevertheless, we do not expect ISO-2 kits to be a better long-term option than ARCS to transport rigid cargo and fleet-support modules efficiently at −28 ± 5°C. The steel skis on ISO-2 kits conduct away frictional heat, and the kits are much heavier than ARCS for the same payload capacity.

Given that their tare weight includes a rigid deck, tube-in-pouch ARCS achieve high payload fractions (0.80–0.83). We expect ARCS resistance per unit weight eventually to approach that of bladder sleds owing to their similar compliant, low-pressure contact with snow. Consequently, the payload-efficiency advantage of ARCS over steel cargo sleds (including ISO-2 kits) should also approach 10:1 over the cold, soft snow of the Polar Plateau.

ARCS provide other advantages compared with steel cargo sleds. Their flat decks and compliant suspensions produce a very gentle ride and permit easy grouping of sleds to accommodate large loads. ARCS are thus well suited to carrying prefabricated facilities or large, sensitive science equipment and thereby save field-assembly labor costs in addition to providing a cost-per-pound savings relative to airlift delivery. Furthermore, ARCS can provide efficient housing and laboratory sleds for light science traverses.

Importantly, ARCS are also less expensive to buy than corresponding steel sleds. The original ISO kits cost about $100,000 (2002), ISO-2 kits cost about $70,000 (2012–13), and ARCS currently cost about $30,000, all with similar payload capacity. As with bladder sleds, ARCS embody the performance gains and cost reductions possible through the introduction of lightweight materials and improved understanding of over-snow mobility.

We are aggressively seeking to improve our understanding and modeling of sled–snow sliding friction, the dominant source of towing resistance for lightweight, flexible sleds. Within the next few years, we expect to optimize ARCS to achieve mobility performance similar to that of bladder sleds. Concurrently, we are gaining experience with durability issues, and performance specifications needed to extend the useful lives of the constituent materials in bladder sleds and ARCS. Collectively, these efforts should complete the transformation of polar resupply traverses from heavy steel sleds to efficient, lightweight, flexible sleds.

1 Introduction

1.1 Background

The National Science Foundation's Division of Polar Programs (NSF-PLR) operates the U.S. Antarctic Program (USAP) to conduct scientific research in Antarctica. McMurdo Station, on Ross Island, is USAP's largest facility, and it serves as the resupply hub for the Amundsen-Scott South Pole Station located 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.

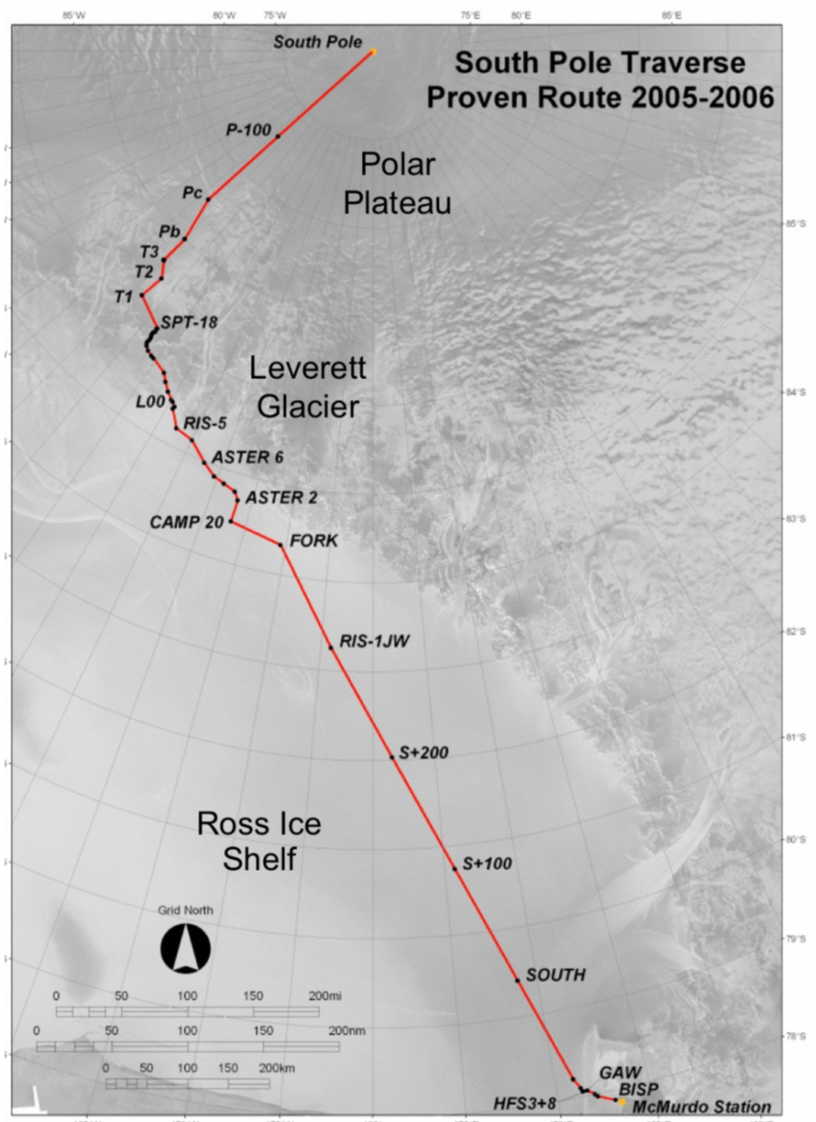
Beginning in 2003, USAP initiated a four-year effort to develop a heavy-haul traverse to resupply South Pole Station from McMurdo Station. Four rubber-tracked tractors and one bulldozer towed steel sleds carrying fuel, cargo and support modules directly over unprepared snow. This proof-of-concept effort 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). It also made the first modest over-snow resupply of South Pole Station. 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 high molecular weight polyethylene (HMW-PE). Compared to 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).

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 and achieved a net economic benefit of \$2.0M/year (Lever and Thur 2014).

Based on this success, USAP expanded SPoT to include a second eight-tractor fleet (SPoT2) and added traverse fleets to support science camps on the Pine Island Glacier (PIG) in West Antarctica and the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) on the Ross Ice Shelf. NSF-PLR also initiated the Greenland Inland Traverse (GrIT) to re-supply its science stations on the Greenland ice cap from Thule Air Base (Lever and Weale 2011).

Figure 1. The SPoT proven route, 1030 miles one way from McMurdo to South Pole.



RADARSAT-1 Image © Canadian Space Agency; Published 2002

1.2 Objectives

CRREL has continued to assist these NSF-sponsored polar traverses to measure and understand the mobility performance of their tractor–sled trains. Goals include improved efficiency and lower life-cycle costs achieved through the innovative use of new materials and designs (Lever 2011a; Lever and Weale 2012; Lever et al. 2012, 2014b; Weale et al. 2015). NSF-PLR, SPoT, PIG, WISSARD, GrIT, and CRREL all collaborate to identify the most pressing issues and the most promising solutions. Consequently, sled development has proceeded rapidly.

1.3 Approach

This report summarizes sled developments and describes recent improvements, performance data, insights, and future goals for sled technology, with emphasis on their impact on Antarctic traverses. It is divided into sections to summarize the advances in fuel sleds and cargo sleds separately.

2 Fuel Sleds

The initial development efforts for SPoT focused on improving the efficiency of fuel sleds because fuel was expected to be SPoT's primary payload. The proof-of-concept fleet began with steel fuel sleds towed in line with the tractor. Early mobility tests demonstrated that simple revisions, such as using a spreader to tow these sleds outside of the tractor ruts or using wider skis with more gentle entry angles, could significantly reduce their towing resistance (Lever et al. 2004, 2006). The proof-of-concept program ended with a demonstration of the potential efficiency and cost advantages of innovative fuel-bladder sleds compared with steel fuel sleds (Lever et al. 2006; Weale and Lever 2008). USAP agreed to fund the rapid development of these promising sleds (Figure 2).

Figure 2. SPoT04-05* steel fuel sleds (*upper*) and SPoT09-10 bladder sleds (*lower*). The tanks and bladders each hold 3000 gal. of fuel, and the images show a full outbound load for a SPoT towing tractor. Accounting for the approximately 6000 gal. each tractor consumes per round trip, bladder sleds triple the SPoT fuel delivery to South Pole from 6000 to 18,000 gal. per tractor. The red spreader bar allows each tractor to connect easily to multiple sleds.

*Note that we use SPoT04-05 to denote the 2004–05 season for SPoT (and likewise for GrIT).

2.1 Fuel-bladder sleds and the role of sliding friction on towing resistance

Lever and Weale (2012) describe the development of fuel-bladder sleds and the mobility theory underlying their performance advantage relative to steel fuel sleds. Briefly, average towing resistance, R, consists of sliding friction and snow-compaction resistance (assuming no undercarriage parts plow through the snow). A simple equation can help guide design choices:

$$R = \left(W_t + W_p\right)\left(\mu + 2p_0/kL\right), \tag{1}$$

where

W_t = tare weight,
W_p = payload weight,
μ = sliding friction coefficient,
p_0 = ground pressure,
k = snow strength from plate-indentation tests, and
L = sled contact length.

To minimize towing resistance for a given payload weight and snow strength, we want to minimize tare weight, sliding friction, and ground pressure and to maximize sled length.

The parameter group $2p_0/kL$ in Equation (1) represents the resistance developed as the sled compacts (crushes) the snow to produce ruts. This term can be large for steel sleds because the stiff skis generate high local pressure over uneven terrain, and it is impractical to make very large steel skis to reduce p_0 and increase L. That is, steel construction is heavy and produces high snow-compaction resistance. By comparison, flexible bladder sleds have a very low tare weight, low ground pressure, and a long contact length and they conform to uneven terrain. They produce negligible snow-compaction resistance and essentially no ruts. Sliding friction thus governs their towing resistance. Table 1 summarizes the differences in physical parameters for steel and bladder fuel sleds.

Measurements are essential to understand and optimize the performance of polar sleds. We began systematic mobility measurements in 2004–05, and our standard instrument package has evolved to include a custom-made 50,000 lb load pin to measure towing force directly at the tractor hitch; a GPS (Global Positioning System) receiver for position, speed, and altitude; and a datalogger to record these values (1 Hz sampling with stored 10 s to 1 min averages and standard deviations).

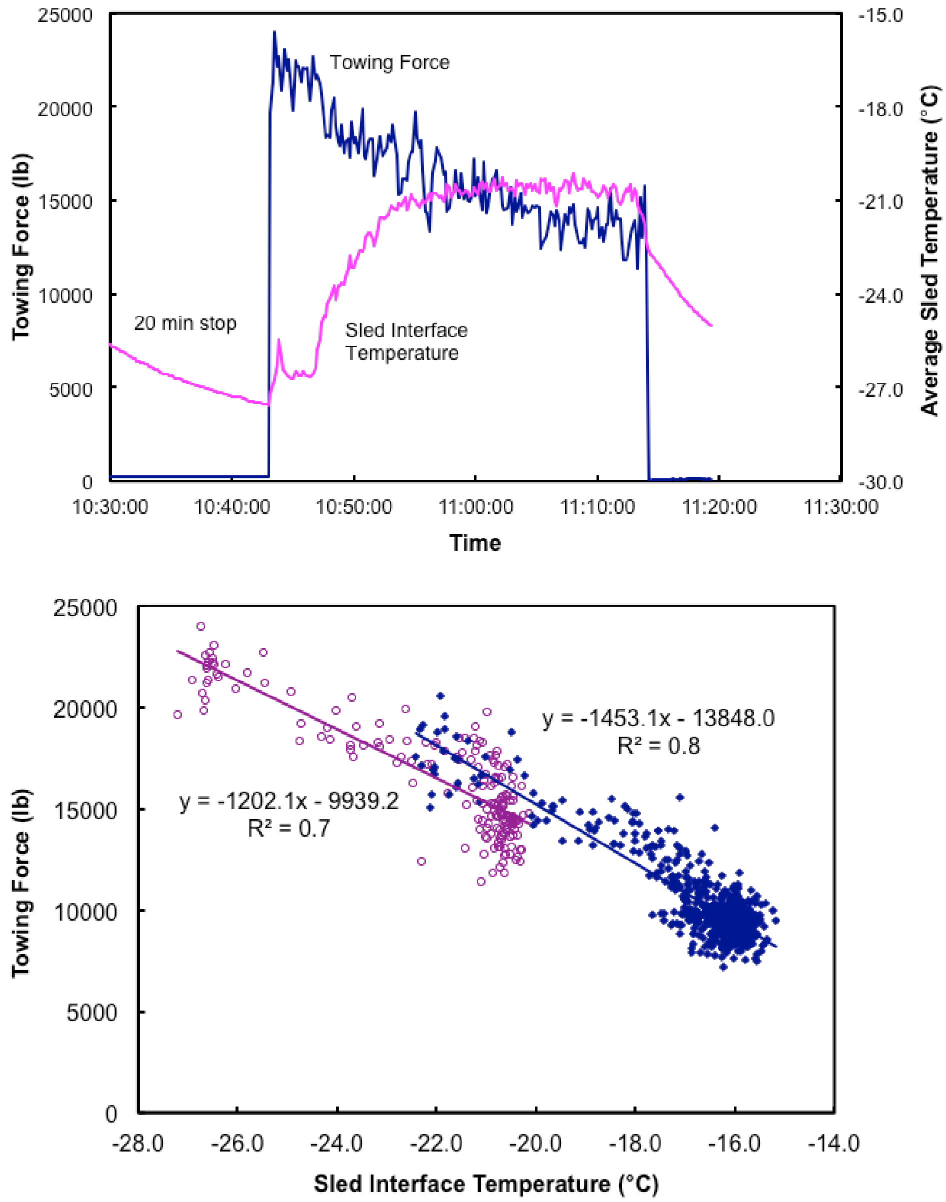
Table 1. Physical parameters for SPoT fuel sleds. The tare weights omit spreader bars, and fuel density is assumed to be 7.0 lb/gal. The gross sled weight is $W = W_p + W_t$.

Parameter	Steel Fuel Sled	Bladder Sled
Capacity (gal.)	3000	3000
Payload Weight, W_p (lb)	21,000	21,000
Tare Weight, W_t (lb)	12,500	1100
Gross Weight, W (lb)	33,500	21,100
Payload Fraction, W_p/W	0.63	0.95
Tare Fraction, W_t/W	0.37	0.05
Contact Length, L (ft)	16	28
Ground Pressure, p_0 (psi)	2.4	0.91

SPoT08-09 was the first large-scale deployment of fuel-bladder sleds, with the fleet of eight tractors towing sixty 3000 gal. and two 2000 gal. fuel bladders outbound from McMurdo. Lever served as crew on SPoT08-09 to operate a tractor, maintain the mobility instruments, and observe sled-train mobility across the entire outbound leg. On that trip, during start-up on cold days (less than −20°C), we measured towing forces that were double the eventual steady-state resistance for bladder-sled trains. These start-up values could cause tractors to break traction during the 10–30 min needed for the sleds to “warm up.” Stops for lunch or other breaks could recreate this transient behavior (with slightly shorter warm-up periods). We suspected that frictional heating, 1–3 kW/m^2 of sled area, was responsible for the lower steady-state towing resistance of the bladder sleds relative to start-up values.

To confirm and quantify the role of frictional heating, we installed thermocouples along the length of bladder sleds beginning with SPoT09-10 and GrIT10. The thermocouple junctions were flush with the lower surface to measure sled–snow interface temperatures (Lever 2011a; Lever and Weale 2012). Mobility tests during staging of SPoT09-10 showed that towing force, and thus sliding friction, was strongly correlated to interface temperature during start-up (Figure 3). Air temperature was essentially constant during these short-duration tests, so the measured sled warming was due entirely to frictional heating.

Figure 3. The measured towing force and average sled–snow interface temperature during start-up for eight tan bladders during SPoT09-10: (*upper*) a time series measured on 19 October 2009 at an air temperature of −30°C; (*lower*) a scatter-plot of data from the 19 October start-up (*purple*) and a similar start-up on 29 October 2009 at an air temperature of −22°C (*blue*). Noise in the data reflects resistance variations over rough snow (sastrugi) along the route. As shown by the best-fit curves, towing force decreased 1200–1500 lb per degree Celsius temperature increase during start-up.



From experiments conducted en route during GrIT10, we obtained more comprehensive measurements to investigate methods to enhance warming of the sled–snow interface (Lever 2011a). We instrumented two bladder sleds with thermocouples and used separate load pins between the sleds and the spreader to measure their towing resistance independently. One sled had electric heating blankets (300 W/m^2) under tan bladders. The blankets were insulated on their upper surfaces to heat the HMW-PE sheet preferentially. We obtained data with the heaters on and off (insulation only). The other sled had thin black covers wrapping the bladders to increase solar gain.

Figure 4 shows the GrIT10 results for steady-state (post start-up) sled resistance per unit weight, R/W, which is equivalent to a friction coefficient for negligible snow-compaction resistance, via Equation (1). For all three warming methods (heaters on, heaters off, black covers), the measured spatial-average sled–snow interface temperature, T_{sp}, collapsed the R/W data reasonably well.

Figure 4. The steady-state sled resistance per unit weight (R/W) versus the spatial-average sled–snow interface temperature (T_{sp}) for tan bladder sleds during GrIT10. Sled1 had heating blankets under the bladders; Sled2 had black covers wrapped around the bladders.

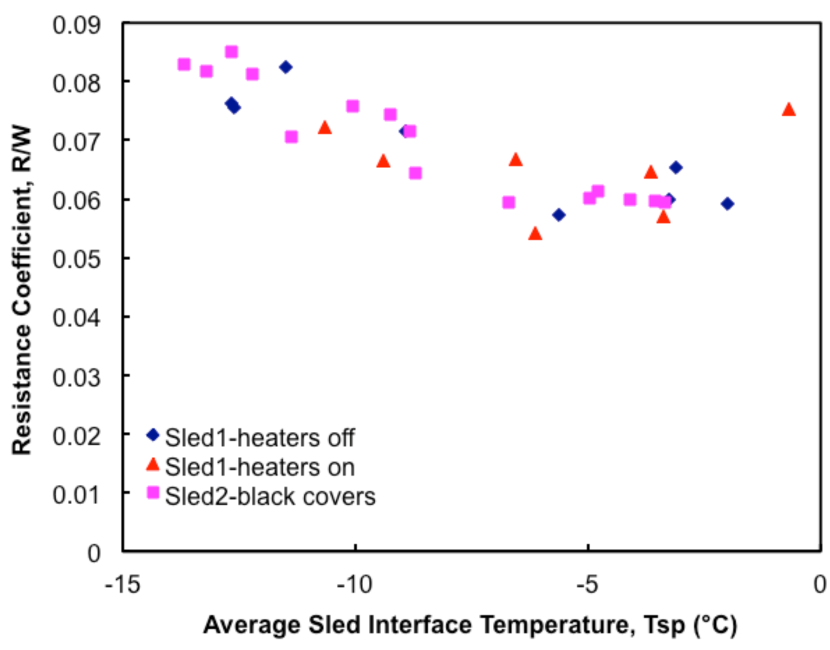
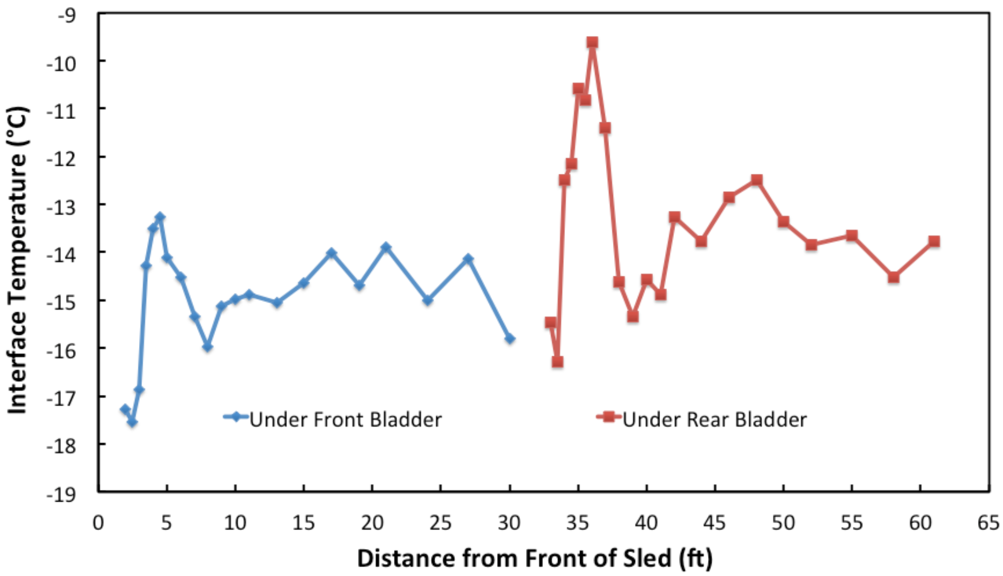


Figure 5 shows a snapshot of the spatial temperature distribution along a GrIT10 bladder sled (Sled1-heaters off) 5 min after start-up at −17.4°C. Under the first 5.5 ft of the front bladder, interface temperature rose 4°C and then dropped 3°C before warming more gradually towards the rear of the bladder. As with SPoT09-10, these sleds consisted of two 3000 gal. tan bladders in line on the same HMW-PE sheet with about a 6 ft gap between them. The pattern repeated under the rear bladder at slightly higher temperatures. The temperature rise from the front to the rear of the sled was nearly 4°C.

Figure 5. The instantaneous temperature distribution along the sled–snow interface for a GrIT bladder sled on 7 May 2010 5 min after start-up. The air temperature was −17.4 °C and the speed was 4.9 mph.



The theory of snow and ice sliding friction (Colbeck 1988, 1992; Lehtovaara 1989; Baurle et al. 2007; Kietzig et al. 2010) provides guidance to interpret these results although the measurements are unique in terms of slider length and polar snow conditions. Cold, dry snow enters under the front of a bladder sled. The local friction (resistance) coefficient can be similar to sliding on sand ($R/W \approx 0.3$), but the actual sled–snow contact area is very small, probably less than 1% of the nominal sled area (Theile et al. 2009). High frictional heating at the contact points leads to rapid temperature rise and melting of contacting snow grains. The resulting meltwater layer then lubricates the sled–snow interface, and resistance consequently drops. Viscous shearing in the meltwater layers eventually dominates local sliding friction, and the sled slowly warms up in response to the frictional heating. For snow-surface temperatures (or air temperatures) near 0°C, excess production of meltwater along the sled can increase local sliding friction via hydrodynamic suction. Throughout the process, the heat available to warm and melt contacting snow grains along the sled interface depends on the difference between the frictional heat production and the heat conducted away through the snow and the sled. That is, the entire thermal budget of the sled–snow system plays a critical role in sliding friction and hence sled towing resistance.

SPoT and GrIT operate mainly over cold-snow conditions (snow temperatures below about −5°C), where warmer sleds should slide easier than colder ones owing to increased meltwater production. Figure 3 confirms this behavior during cold start-up transients, where sled warming is solely due to frictional heating. Figure 4 confirms that steady-state resistance also decreases with increasing average sled–snow interface temperature until the latter warms to about −5°C. Here, the entire thermal budget (air temperature, solar gain, convective cooling, heating/insulating, etc.) influences sliding friction over hour-long time scales, and average interface temperatures reasonably collapse these effects. Figure 4 also shows that steady-state resistance levels off or rises for higher interface temperatures, perhaps from excess meltwater production.

The spatial distribution of interface temperature along the sled, shown in Figure 5, complicates the picture slightly. The abrupt temperature drop after an initial rise was a surprise and has not been reported before for sliders on snow or ice. We speculate that dry friction at the front produces flash melting and abundant meltwater, which then abruptly deceases friction and attendant heating before establishing a more gradual meltwater development. The 6 ft gap between bladders is apparently sufficient to cool the snow surface back to near-ambient temperatures before the pattern repeats under the second bladder. Clearly, the frictional processes operate at a spatial scale much smaller than the sled length (i.e., sled–snow contact points), and quantitative understanding must begin there. Nevertheless, the data confirm that the general theory of snow and ice friction can qualitatively describe the towing resistance of bladder sleds.

2.2 Guidance from numerical modeling of snow friction

Although the theory for sliding friction describes processes acting at the microscale (e.g., sub-millimeter snow-grain contacts), to date these processes have been aggregated to macro (centimeter) spatial scales to enable practical simulations.

Kaempfer and Lever (2009) simulated the spatial and temporal development of sliding friction for bladder sleds by implementing the method of Baurle et al. (2007). The resulting sled–snow macro-model used the following assumptions and simplifications:

- The sled consisted of a polyethylene sheet of length l, thickness d, and width w moving along l at a horizontal velocity v. The problem was assumed two-dimensional in space, $l \times d$.
- The sled moved on a flat, horizontal snow surface, and the snow entering below the front of the sled was at a constant temperature, T_0.
- Owing to snow porosity, the sled–snow contact area was smaller than the sled area (approximately sled area times snow density). For heat conduction purposes, the sled and snow were in perfect contact over that area.
- At the sled–snow interface, temperatures were matched, frictional heat was generated, and heat was conducted away into the sled and snow.
- If the interface temperature was below a given threshold ($T < T_m$), dry friction was assumed with a friction coefficient typical for polyethylene on ice (about 0.3). If $T > T_m$ at the interface, the net difference between heat produced and heat conducted away caused snow to melt and thereby produced a liquid film at the interface.
- The macroscale melting temperature, T_m, was assumed to be the spatial average of 0°C over the contact area and T_0 in the pore spaces.
- If a liquid film was present, friction (and heat generation) was due to viscous shearing of the water film under Couette flow:

$$\mu_v = \frac{\eta V A_c}{h_w F_n}, \tag{2}$$

  where μ_v is the viscous-shearing friction coefficient, η is water viscosity, V is slider velocity, A_c is contact area, h_w is water-film thickness, and F_n is normal load.

- The bottom boundary condition (snow) was chosen so that the snow depth did not influence the results. The top boundary condition (top of the sled) was held at the constant air/snow temperature T_0, owing to the high thermal mass of the fuel bladder.
- Sled velocity could be varied during a simulation to reflect tractor–sled speed changes.

No observations are available in the literature of actual snow–slider contact area or its evolution after sliding begins. Kaempfer and Lever (2009) thus assumed constant contact area or area ratio, $AC = A_c/A_{sled}$, throughout each simulation but varied it between simulations to assess its effects. Other than this, there were no tuning parameters in their model. They produced only a small number of simulations, focused on the start-up transients for bladder sleds at −30°C for which SPoT towing-resistance data were available.

Figure 6 shows cross sections at the front and rear of a dual-bladder fuel sled, 56 ft long, from partway through a simulation. The sled and snow both warmed up in response to frictional heating, and the model captured the spatial and temporal changes. As expected, the sled and snow were warmer towards the rear of the sled, and the sled was warmer than the snow because the model simulated fresh, cold snow constantly entering at the front of the domain. The model also showed that the front of the sled–snow interface remained too cold to be lubricated, while the lubricating layer increased significantly in thickness towards the rear of the sled.

Figure 6. Simulation results from Kaempfer and Lever (2009) showing cross sections through the sled–snow interface at the front and rear of a dual-bladder fuel sled (*left* and *right* images, respectively). Each colored domain is 5.9 in. long and 0.9 in. high (*blue* = cold, *red* = warm). Warming from frictional heating at the interface is clearly visible in both locations.

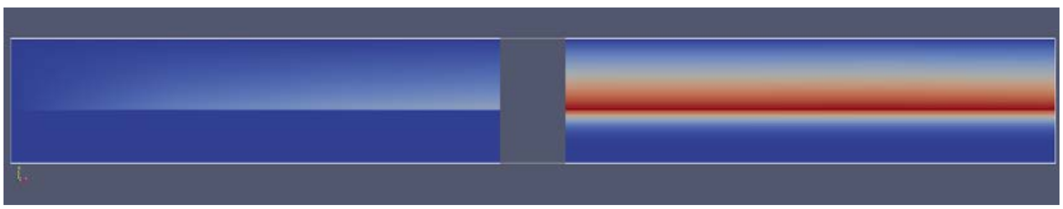
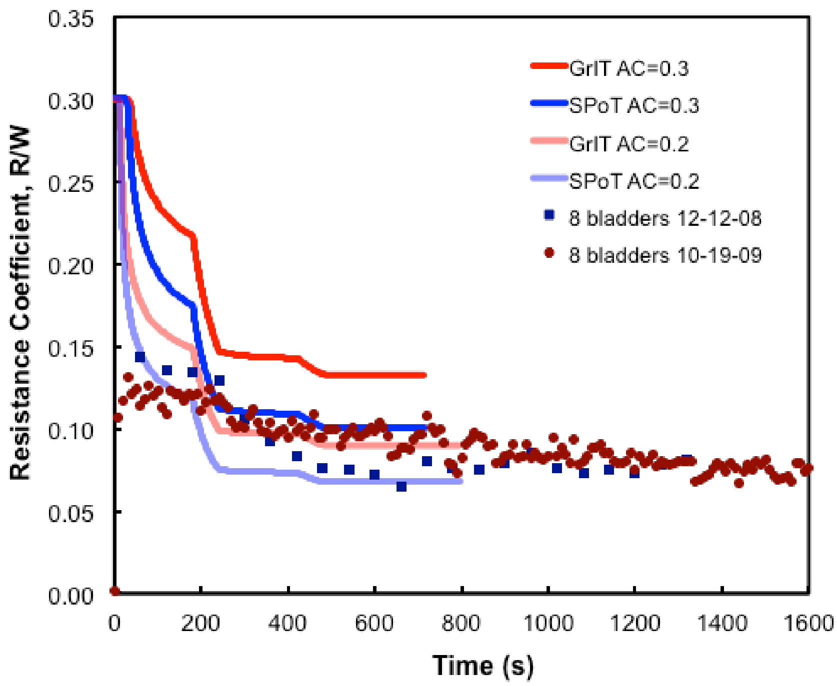


Figure 7 compares four sets of simulated start-up transients with towing-resistance data from SPoT08-09 and SPoT09-10 at a −30°C air temperature (Kaempfer and Lever 2009). The simulations examined the effects of assumed contact area (*AC* = 0.2 and 0.3) and single versus dual in-line bladders (GrIT and SPoT, respectively). Given the lack of tuning parameters, the model yielded good agreement for the overall duration of start-up transients and the ultimate steady-state resistance. These results suggest that indeed the sled–snow thermal regime governs sliding friction and thus towing resistance for bladder sleds. However, the model over-predicted start-up resistance and did not predict the abrupt rise–fall of temperature at the front of a sled or between bladders on a dual-bladder sled. The evolution of actual sled–snow contact could account for these discrepancies.

Figure 7. Measured and modeled resistance coefficients for bladder sleds (Kaempfer and Lever 2009). The data are for SPoT sled trains consisting of eight tan 3000 gal. bladders (two in line per sled) at a −30°C air temperature. The model results are for two in-line bladders (SPoT) and a single in-line bladder (GrIT) to reveal the role of slider length. The contact-area ratio (*AC*) was constant at 0.2 or 0.3 throughout each simulation.



Although meltwater development clearly depends on actual contact area, no observations exist to guide modeling of contact-area evolution along a slider. Nevertheless, the simulations revealed an important effect: a smaller constant contact area (*AC* = 0.2 vs. *AC* = 0.3) produced higher temperatures, more rapid meltwater development, and thus lower resistance. Because the initial area ratio is probably less than 0.01 (Theile et al. 2009), flash heating and melting must occur along the sled at the onset of motion and near the front of the sled at all times. Lower start-up resistance and spatially varying local resistance (as per Figure 5) are thus likely to result. We intend to simulate the evolution of contact area in a revised friction model.

Interestingly, the model simulations also revealed the important role of sled length. For its inaugural traverse in 2008, GrIT towed four single-bladder sleds in a four-across configuration with each 3000 gal. bladder on a separate HMW-PE sheet. For a single-bladder sled (labeled GrIT in Figure 7), the model predicted about a 30% higher resistance per unit weight compared with a dual-bladder sled (SPoT). Indeed, GrIT08 bladder sleds towed 20%–50% harder than SPoT08-09 ones (Lever and Weale 2011). Longer sleds allow for more sled–snow contact time, more frictional heating, higher temperatures under the rear bladder, and thus lower overall resistance per unit weight. Based on our recommendations, GrIT switched to dual-in-line bladders for its second traverse in 2010. Average bladder-sled resistance decreased 30%–60%, and some of this decrease likely resulted from the longer sled length (Lever 2011a).

Friction theory and model results also highlighted an important positive feedback: higher towing speeds increase frictional heating, which increases meltwater production, lowers towing resistance, and thereby permits higher tractor speeds for a given engine power. The abrupt break points in the simulation curves in Figure 7 occurred at speed increases programmed to mimic tractor shift changes. Predicted resistance dropped at each speed increase. To capitalize on this effect, we recommended that SPoT and GrIT tractor operators attempt to pull at maximum engine power at all times after the initial start-up, shifting upwards as resistance drops until no further gear increases are possible. Available traction will still limit the total sled load that a tractor can tow from a standstill (the coldest and highest-resistance state), but for a given engine power and fuel consumption, the recommended procedure will result in the shortest start-up transients and the highest average travel speeds. The tractor operators have generally adopted this recommendation and report good results.

We have recently begun a basic-research project to investigate and model sliding friction on snow on the microscales at which the key processes operate (Lever et al. 2014a). Among other objectives, this project will seek to quantify the evolution of real contact area; to develop and validate a microscale simulation model; and to parameterize microscale processes to enable accurate quantitative modeling of macro-scale systems, such as fuel-bladder sleds.

2.3 Engineering warmer sleds: black bladders and passive solar gain

Guided by theory, numerical simulations, and the GrIT10 field experiments, we assessed several options to warm bladder sleds to reduce their towing resistance.

The construction-grade electric heating blankets tested on GrIT10 each produced 1750 W over the 5 × 11 ft contact area (340 W/m^2), and we used two blankets under each bladder. For a set of eight bladders, electric blankets would consume 28 kW and require a substantial generator (perhaps 40 kW to allow for altitude de-rating on the Polar Plateau), adding cost and tare weight. An optimized approach might place heaters under only the front few feet of each bladder to eliminate those regions of dry friction. We will assess this option once we have improved our friction-modeling capabilities.

Glycol-warmed construction-grade heating blankets are also available and could use the waste heat from a tractor's cooling system to power them. However, we judged that long glycol loops from the tractors to the sleds posed reliability and environmental concerns related to the risk of leaks.

We decided that passive solar gain, obtained by using black rather than tan bladders, was the most attractive near-term option. The GrIT10 experiments with black bladder-covers (Lever 2011a) and analyses based on a one-dimensional, transient energy-budget model suggested that black bladders could provide significant resistance reductions. Both SPoT and GrIT operate during polar summers, when sunlight is essentially available 24 hours per day. Initial discussions with the bladder manufacturer (Aero Tec Laboratories [ATL]) indicated that they could produce black bladders at a similar cost as tan ones by using similar polymer-coated fabric and identical fabrication methods. Their only requirement was to receive a sufficient order to purchase a batch of black material from their supplier. We thus recommended that SPoT and GrIT coordinate procurements of black bladders to satisfy this requirement and thereby improve fuel-sled efficiencies for both traverses.

For 2010-11, SPoT purchased eight black ATL fuel bladders and assembled them into a sled train to assess the efficiency gain from passive solar heating (Figure 8). We then conducted pre-departure, head-to-head mobility tests of eight tan and eight black bladders over natural snow along a section of SPoT's route from Williams Field to the Shear Zone crossing (designated BISP to GAW in Figure 1). Both tractor–sled trains included full suites of mobility instruments. Table 2 summarizes the results.

Figure 8. A set of eight black bladders on four black HMW-PE sleds. The left-most sled in this image was instrumented to measure the sled–snow interface, fuel and air temperatures, and solar irradiance. The towing tractor logged towing resistance, speed, location, and altitude.

Table 2. A performance comparison of eight black bladders and eight tan bladders during runs on 28 October 10 to stage them across the shear zone. The tare weight for each sled train includes a spreader (3900 lb).

	Black Bladders	Tan Bladders
Sleds (four each)	8 ft x 68 ft x 0.5 in. black HMW-PE	
Payload	24,000 gal. fuel	
Payload Weight, W_p (lb)	168,000	
Tare Weight, W_t (lb)	12,700	
Gross Weight, W (lb)	181,000	
Payload Fraction, W_p/W	0.93	
Max 1 min Start-up Resistance, $R_{1\text{-}min}$ (lb)	13,200	14,100
Start-up Duration to Steady State (min)	3.2	2.0
Steady-State Speed (mph)	7.8	8.1
Steady-State Resistance, R (lb)	5500	9900
Average Resistance Coefficient, R/W	0.030	0.055
$T = R + 3\sigma_R$ (lb)	7500	11,500
Total Resistance Coefficient, T/W	0.042	0.064
Payload Efficiency, W_p/T	22.3	14.6
T_{air} (°C)	−21.0	−20.9
T_{fuel} (°C)	−10.5	−14.6
T_{sled} (°C)	−10.6	−11.3
P_{solar} (W/m^2)	356	366

Table 2 includes several measures that are helpful to characterize sled mobility. As noted, average resistance, R, is essentially identical to average sliding friction for bladder sleds (negligible snow-compaction resistance), and R/W is thus the average sliding-friction coefficient. To account for resistance variations caused by snow roughness and strength variations, we use total resistance $T = R + 3\sigma_R$ for load planning, where σ_R is the standard deviation of R. The total resistance for a sled train must be less than the tractor's drawbar pull on that terrain to avoid frequent immobilizations at resistance peaks. Gross sled weight, W, consists of tare weight, W_t, and payload weight, W_p. Payload fraction, W_p/W, indicates what proportion of the total sled weight is dedicated to payload. Tare fraction is $W_t/W = 1 - W_p/W$. A useful overall performance measure is payload efficiency, defined as achievable payload weight per unit of towing force, W_p/T. It combines the benefits of a high payload fraction and low towing resistance.

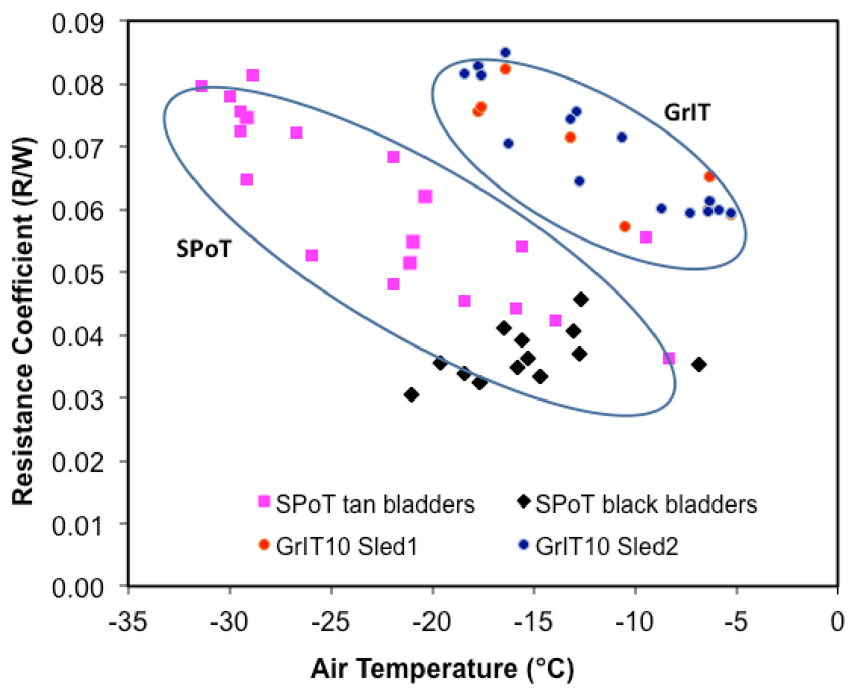
As shown in Table 2, the performance of the tan bladders was quite good (T/W = 0.064) and consistent with SPoT08-09 and SPoT09-10 measurements at similar air temperatures. The performance of the black bladders (T/W = 0.042) was remarkably good. The recorded solar input suggests essentially clear skies during the entire run to the shear zone. During the test interval (1330–1400 hours), fuel in the black bladders was 4.1°C higher than fuel in the tan bladders and almost 11°C higher than the air temperature. This provided a large heat input to warm the sled, and T/W dropped by approximately one-third compared with the tan bladders. The corresponding payload efficiency jumped 53%, indicating that for the same towing effort, a tractor could tow 12 black bladders rather than 8 tan ones.

With a goal of comparing the performance of black and tan bladder sets across the entire route, SPoT10-11 departed McMurdo with these two instrumented tractors-sled trains. Unfortunately, the instrumentation cable on the tan-bladder sled train failed immediately, and the cable on the black-bladder set failed a few days later (broken connectors). Consequently, data are available only for black bladders towed across the Ross Ice Shelf.

Figure 9 summarizes the SPoT10-11 results relative to earlier data from SPoT and GrIT. All data are for dual-in-line bladders. Here we plot R/W against air temperature to include SPoT08-09 and SPoT09-10 data, which lack sled-temperature measurements. The data are more scattered than in

Figure 4 because several heat-transfer processes influence sled-interface temperatures, but they are nevertheless quite useful. The black-bladder data confirm that passive solar gain can provide valuable reductions in towing resistance, especially at lower air temperatures.

Figure 9. Resistance versus air temperature for SPoT and GrIT (unheated) bladder sleds. The SPoT10-11 black-bladder sleds displayed the lowest resistance and a large performance advantage over tan bladders at low temperatures.



Interestingly, the GrIT sled-resistance data all plot higher than the SPoT data at the same air temperatures. Because GrIT10 used dual-in-line bladders, sled length cannot account for this difference. We speculate that softer Greenland snow requires more actual contact area to support the sleds, which spreads frictional heating over more snow grains and thus reduces meltwater production. This effect of snow strength on sliding friction has not been systematically investigated or incorporated into snow-friction theory. We intend to explore the role of snow strength on sliding friction through our basic research investigation (Lever et al. 2014a).

2.4 Using black bladders to increase SPoT efficiency and payback

The data in Figure 9 suggest that a SPoT tractor could tow 12–16 black bladders, in steady state, for air temperatures common across the Ross Ice

Shelf. An economic analysis by Lever and Thur (2014) showed that increasing SPoT's outbound loads to 12 bladders per tractor from the 2008–11 average of 9 bladders per tractor would increase the delivered payload by 58% and more than double the net annual benefits to $4.6M/year. Because SPoT already covers its costs, efficiency increases produce large increases in net benefits. However, three tractors on SPoT08-09 each towed 12 tan bladders outbound from McMurdo, and they frequently experienced immobilizations during start-up. Is it possible to increase the per-tractor sled load using black bladders without substantially increasing en-route immobilizations and consequent schedule delays? We sought to address this question starting in 2011–12.

In 2011–12, USAP added a second fleet of eight towing tractors to the South Pole Traverse, designated SPoT2, and renamed the original fleet SPoT1. The numbering also reflected their intended sequence of departure from McMurdo. SPoT1's principal season objective was to recover equipment from a deep-field science camp (Antarctic Gamburtsev Province [AGAP]) located 422 miles beyond South Pole. It would then return to South Pole, deliver its excess fuel, and then continue back to McMurdo. SPoT2's objectives were initially modest: assemble and test its tractors and sleds, and then shuttle fuel to support WISSARD, a deep-field science camp 74 miles off the SPoT route near the southern end of the Ross Ice Shelf. However, USAP reprogrammed SPoT2 early in the season to execute a fuel delivery to South Pole as its main mission. It would then establish the route segment to WISSARD and recover some cargo during its return leg to McMurdo.

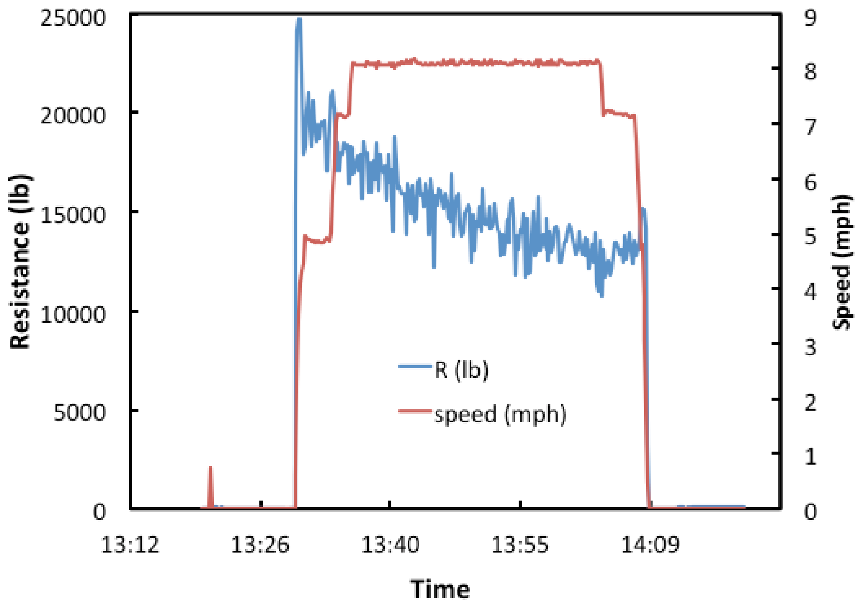
Owing to its more remote objective, SPoT1 was equipped mostly with newly acquired black bladders to minimize towing resistance across unknown terrain conditions from South Pole to AGAP. SPoT2 used mostly older, tan bladders. We instrumented one tractor in each fleet with a load pin, GPS receiver, air-temperature sensor, and datalogger to document season performance. The measurement suite did not include thermocouples to measure sled temperatures, but it was sufficient to correlate sled resistance with air temperature (per Figure 9).

Prior to SPoT1's departure, we conducted mobility tests on black-bladder sled trains along the route to the shear zone. The first trial was on 20 October 2011 at an average air temperature of −29°C. Two sets of eight black bladders were filled and then staged adjacent to Williams Field. One set was filled on 17–18 October and the other set on 19 October. The set filled on 19 October had less than 24 hr to warm up from the over-winter temperature of the McMurdo storage tanks. We connected the rear set of eight bladders through a long plasma rope to the spreader bar of the front set of eight (Figure 10). The rope had some slack to allow the front set to move first. However, the instrumented tractor (Agco MT865 with crane) was not able to tow the combined train of 16 bladders. It generated a very respectable 10 s drawbar pull of 28,000 lb before breaking traction. We connected a second tractor (Case 535 Quadtrac) for a tandem tow of the 16 bladders. Peak start-up resistance was approximately 49,000 lb, and resistance decreased to roughly 37,000 lb ($R/W \approx 0.10$) over the next 20 min with the tractors achieving 7.5 mph. These towing forces are well outside the drawbar capacity of one tractor.

Figure 10. Sixteen black bladders staged for mobility tests along the shear zone route on 20 October 2011.

After about 30 min, we stopped and separated the two sets of eight bladders to tow them separately back to Williams Field. Figure 11 shows the resulting resistance and speed data. Resistance decreased from nearly 25,000 lb at start-up to approximately 13,000 lb after 40 min, at which point the tractor slowed to turn the bladders around. The tractor was able to achieve 8.1 mph at 80%–85% engine power towards the end of the run. If we take this value as steady state, the resulting $R/W = 0.073$ at a −29°C air temperature is similar to data obtained for tan bladders on the Polar Plateau at the same air temperature (Figure 9). This suggests that the fuel had insufficient time to warm up via solar gain, and thus the sleds performed as if they carried tan bladders. Unfortunately, the 2011–12 measurements did not include fuel temperatures, so we cannot confirm that cold fuel was responsible for the high towing forces measured.

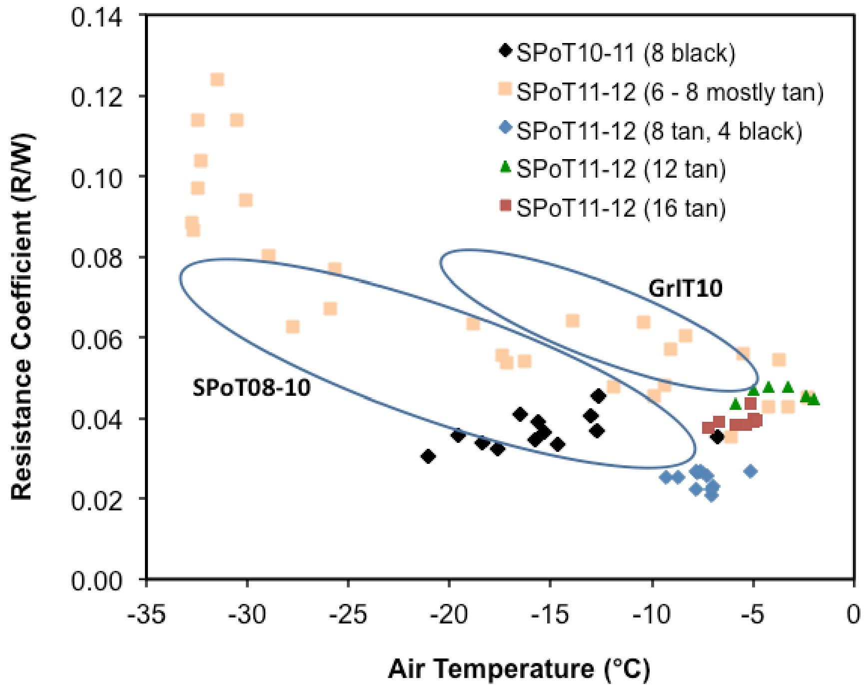
Figure 11. The start-up transient for eight black bladders towed on 20 October 11 at an average air temperature of −29 °C. Resistance data are 10 s average values.



We conducted a second attempt to tow 16 black bladders with one tractor on 29 October 2011. The average air temperature was −22°C. These bladders had 7–10 days to warm up under solar gain, and we again staged the sleds near Williams Field. The second instrumented tractor (Case 530 Quadtrac) connected to the two sets of eight bladders but broke an old plasma rope at a 26,600 lb towing force (10 s average) before the rear set began moving. A second attempt was more successful with the tractor moving both bladder sets for a few seconds before breaking traction (peak 10 s average of 23,900 lb). Separate towing of each bladder set resulted in a steady-state resistance of $R/W = 0.044–0.052$, slightly below the average for tan bladders at the same air temperature (Figure 9). This suggests that solar gain had increased fuel temperatures but not significantly.

One instrumented tractor departed with SPoT1 on 4 November 11 towing eight black bladders. Unfortunately, for several days, the operator installed the load pin backwards in the drawbar hitch. By the time this was corrected on 15 November 11, the tractor had switched sled trains and was towing a train consisting of six tan and two black bladders. The resulting resistance data plot high relative to SPoT08-10 data, especially below −30°C over the Polar Plateau (Figure 12). We do not know the reason for the higher resistance coefficients other than that the operator noted soft snow on the Polar Plateau. Again, soft snow could increase actual sled contact area and slow the rate of meltwater production. Plotting resistance data against air temperature does not capture this effect.

Figure 12. SPoT11-12 bladder-sled resistance coefficients relative to SPoT08-10 and GrIT10 groupings (*ovals*). Tractor 289 (SPoT2) successfully towed sled trains consisting of 12–16 tan bladders on the Ross Ice Shelf and achieved very low resistance for 8 tan preceding 4 black bladders.



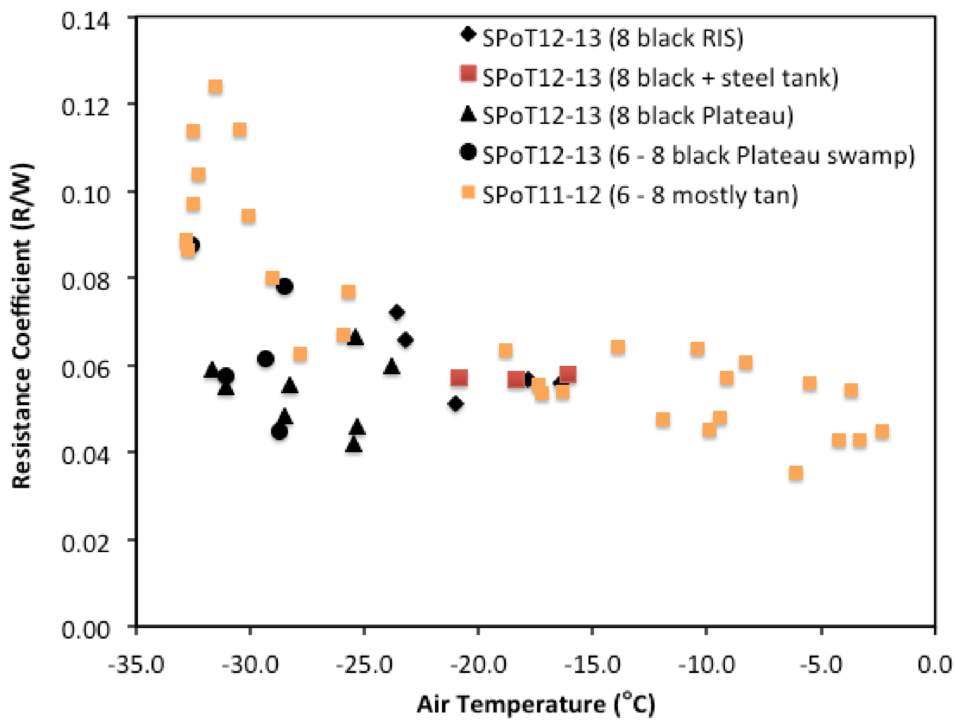
The second instrumented tractor departed on 30 November 2011 with SPoT2, and the fleet quickly ran into a series of mechanical issues. For 13 days (4–20 December), the instrumented tractor towed 12–16 bladders over the Ross Ice Shelf to compensate for mechanical breakdowns of other SPoT2 tractors. This was the first time a SPoT tractor successfully towed 16 bladders in the field, albeit at air temperatures above −10°C. Interestingly, the resistance data show a consistent pattern: the sled train consisting of 8 tan bladders in front of 4 black ones towed much easier than the sled train of 12 tan bladders (lower-right corner of Figure 12). This was a sufficiently strong effect that the tractor operator even noted the qualitative difference in his logbook. Sled trains consisting of 16 tan bladders (two sets of eight) were mid-way in performance. This effect is consistent with snow-friction theory—trailing bladder sleds slide over snow pre-warmed by leading sleds. The effect can be enhanced if the trailing bladders are black and thus warmer than tan ones. Indeed, the resistance coefficients for the sled train of eight tan bladders and four black ones are the lowest yet measured in Antarctica or Greenland (average $R/W = 0.025$).

SPoT2 probably benefited by traveling over snow compacted by the SPoT1 fleet. On firm compacted snow, tractors develop higher maximum drawbar pull, and the sled–snow contact area is smaller to promote more rapid frictional heating. Also, by departing later, air and fuel temperatures on SPoT2 will generally be warmer than on SPoT1. Because SPoT2 will annually gain these benefits, its outbound sled loads could be higher to increase payload delivered and economic payback without increasing immobilization risks.

In 2012–13, the only mobility data on bladder sleds came from an instrumented tractor on SPoT1. It towed 8 full black bladders across the Ross Ice Shelf and 6–8 black bladders across the Polar Plateau (fuel load gradually decreased by daily tractor refueling). Figure 13 shows the measured resistance coefficients compared with the data from SPoT1's mostly tan bladders towed in 20011–12. On average, the set of black bladders towed much better than the set of mostly tan bladders across all conditions. The greatest relative benefit from black bladders was over the most demanding conditions: the cold, soft snow on the Polar Plateau (air temperatures below −25°C in Figure 13).

Interestingly, the 2012–13 black bladders achieved this performance improvement on the Polar Plateau despite having less time for solar gain and encountering lower air temperatures before reaching it. In 2011–12, SPoT1 took 24 days to reach the Polar Plateau, over which time air temperatures averaged −10.4°C. The comparable figures for 2012–13 were 16 days and −18.3°C. Although we do not have corresponding solar-irradiance data, solar gain was apparently sufficient for the black bladders to produce significant in-field performance benefits relative to tan ones.

Figure 13. In 2012–13, SPoT1 towed sets of 6–8 black bladders to South Pole. The data are separated for route segments Ross Ice Shelf (RIS), Polar Plateau, and Plateau Swamp. Towing an empty steel fuel tank behind eight black bladders on the RIS (8 black + steel tank) had little influence on the combined resistance coefficient.



3 Cargo Sleds

Despite SPoT's emphasis on fuel as payload, it does occasionally deliver rigid cargo, and its fleet-support sleds are cargo sleds carrying living facilities, food and power modules, and spare parts. Furthermore, GrIT delivers proportionally more cargo than fuel, and significant cost savings are possible for both polar programs if large facilities (science or infrastructure) can be prefabricated in the U.S. and transported intact to South Pole or Summit.

For these reasons, the Arctic and Antarctic logistics sections of NSF-PLR have jointly supported developing lightweight cargo sleds to seek the payload efficiency of fuel-bladder sleds. CRREL has led this development effort through laboratory tests, design analyses, field tests, and communication exchanges with SPoT and GrIT personnel. The key characteristics sought are low tare weight and a low and uniform ground pressure comparable to values for bladder sleds.

3.1 SPoT's steel cargo sleds

SPoT's proof-of-concept cargo and fleet-support sleds placed modified International Standards Organization (ISO) shipping containers and prefabricated building modules on steel ski kits consisting of steerable, cable-connected front and rear ski assemblies (Figure 14). The first use of these steel "ISO" kits in 2003–04 revealed that they produced high towing resistance and large pitch and roll motions, both of which increased with each successive sled in line (Lever et al. 2004). High resistance led to frequent immobilizations, and large motions led to catastrophic hardware breakage.

Expedient mobility tests suggested the underlying cause (Lever et al. 2004, 2006). At high tractor drawbar pull, track slip disaggregated the otherwise firm snow, and the sled skis rode in the resulting soft snow in the bottom of the tractor's ruts. As resistance increased, the tractor would need to pull harder, which produced more soft snow and even deeper ruts. This process could establish traction-slip-resistance feedback that could quickly immobilize the towing tractors. Furthermore, because the skis could intermittently plow and then ride over piles of the soft snow, sled motions increased with each sled in line (so called "porpoising" behavior). To combat both problems, CRREL recommended increasing the length of the transverse beam (or “bench”) that separated the skis to place the skis outside of the tractor ruts (Figure 15) and increasing the ski size on the module sleds to reduce ground pressure. Towing performance improved considerably in 2004–05 (Lever et al. 2006). These modified ISO kits have served SPoT reliably ever since.

Figure 14. The original 2003–04 steel ski kits (ISO kits) used to support SPoT cargo and fleet-support modules: (*upper*) the coupled living module and generator module; (*lower*) a sled train consisting of a refrigerated food module, a flat rack, and an ISO container known as the tool shed. The skis for these kits rode in the ruts produced by the towing tractors, which produced increasing resistance and motions for each successive sled in line (Lever et al. 2004).

Figure 15. The flat rack and tool shed supported on modified ISO kits during SPoT04-05. Longer benches placed the skis outside of the tractor ruts, but the sleds retained their high tare weight.

The steel ISO kits have physical characteristics that produce important performance disadvantages relative to bladder sleds. Table 3 compares these characteristics with those for bladder sleds. Qualitatively, they include the following:

- High tare weight
- High nominal ground pressure
- High local ground pressure exerted by stiff skis on rough snow
- High thermal conductivity near the snow–ski interface (steel above polyethylene)
- Short slider (ski) length

Table 3. Physical characteristics of a SPoT steel ISO sled (20 ft ISO container) and a fuel-bladder sled for the same payload weight. Cargo sled tare weight includes the ISO container.

Parameter	Steel ISO Sled	Bladder Sled
Capacity	1200 ft^3	3000 gal.
Payload Weight, W_p (lb)	21,000	21,000
Tare Weight, W_t (lb)	25,400	1100
Gross Weight, W (lb)	45,400	21,100
Payload Fraction, W_p/W	0.46	0.95
Tare Fraction, W_t/W	0.55	0.05
Contact Length, L (ft)	9	28
Ground Pressure, p_0 (psi)	2.9	0.91

High ground pressure over natural snow causes snow compaction to be a significant resistance contribution (Equation [1]). Average resistance (R) and resistance variations caused by snow-strength spatial variations (σ_R) both increase with increasing ground pressure. Steel-ski heat conduction and short slider length limit warming of the interface and thus increase sliding friction. Consequently, we would expect steel-ski cargo sleds to have higher resistance per unit weight than bladder sleds. Importantly, these effects cause sled resistance to increase dramatically in the soft, cold-snow conditions found along the last 100 miles of SPoT's route to South Pole. The proof-of-concept crew entitled this region the "Polar Swamp" to reflect the severe mobility problems encountered (Wright 2006).
Besides higher resistance per unit weight (T/W), steel-ski sleds also have a much higher tare weight and hence a lower payload fraction (W_p/W) than bladder sleds. Tractors devote considerable effort to tow the heavy steel sleds in addition to the payload. Consequently, payload efficiency (W_p/T) is much lower than for bladder sleds.

Our experience converting from steel fuel sleds to bladder sleds suggested that both towing resistance and tare weight could be reduced significantly by using lightweight, flexible materials for cargo sleds. Capital costs would also likely decrease compared with steel construction. Although some development risk was involved, NSF-PLR agreed that these potential benefits were worth pursuing.

3.2 Air Ride Cargo Sleds (ARCS)—Initial Prototypes

Beginning in 2010, SPoT, GrIT, and CRREL personnel collaborated to develop high-efficiency cargo sleds. Our approach used air-filled pontoons as a compliant, lightweight suspension between a wood-framed cargo deck and an HMW-PE sheet, with the sled towed via steel tow plates at the front of each sheet as per bladder sleds. We termed these Air-Ride Cargo Sleds (ARCS). The design targets were a 5000 lb tare weight, a 20,000 lb payload weight, and a 1 psi ground pressure. Conceptually, the flat deck could accommodate a range of payloads, including ISO containers, prefabricated modules, and loose-loaded cargo. The air-ride suspension would cushion the payload over rough sastrugi.

To reduce development risks, we tested several prototype ARCS variations in a snow-filled cold room at CRREL (Figure 16). These tests confirmed that the compliant sled would remain stable over rough snow and allowed us to work out attachments between the sled, pontoons, and deck (Lever and Gooch 2010).

Figure 16. A prototype ARCS with 7400 lb of payload tested in a snow-filled cold room at CRREL. Three air-filled pontoons (*blue*) act as a compliant suspension between the 8 ft wide × 16 ft long wooden deck and an HMW-PE sheet (*white*). The sled is seen cresting a 2 ft high snow bump. A programmable cable-drive system allowed cyclical travel along the 120 ft long cold room at speeds up to 5 mph.

Figure 17 shows the SPoT10-11 prototype ARCS deployed only three months after the CRREL tests. Designed to carry SPoT's refrigerated food module, it consisted of two 16 ft wide × 14 ft long wood-framed decks supported by 12 pontoons and straddling two adjacent 8 ft wide sheets of HMW-PE (Lever 2010). The sled displayed excellent ride and stability over 2–3 ft snow bumps taken at speeds exceeding 8 mph. Table 2 summarizes the results of mobility tests of the prototype ARCS and the ISO kit food module that were conducted near Williams Field, McMurdo Station, in October 2010.

Compared with the steel sled it replaced, the prototype ARCS's tare weight dropped from 19,500 lb to 12,500 lb (including the 4500 lb towing spreader), and resistance per unit weight dropped by 60%. Consequently the payload efficiency, or payload weight carried per unit towing force, more than doubled. Unfortunately, to meet the short deployment deadline, we selected off-the-shelf pontoons used for river rafting, and several plastic end caps failed during the first few days of outbound travel. Rather than deal with this complication, SPoT crew swapped the food module back onto its ISO kit to complete the 2010–11 round trip.

Figure 17. (*Upper*) SPoT's refrigerated food module (*white and red container*) on a steel-ski ISO kit; (*lower*) prototype ARCS carrying the same module during mobility tests in October 2010. The module was strapped to two 16 ft wide × 14 ft long wooden cargo decks, each supported by six air-filled pontoons (*blue*) between the decks and the HMW-PE sheets.

Table 4. A performance comparison of a steel-ski ISO kit and a prototype ARCS to transport SPoT's refrigerated food module, based on tests conducted near Williams Field on 21–29 October 2010. Here, the entire refrigeration module is payload.

	Steel ISO Kit	Prototype ARCS
Sled Undercarriage	Steel benches and skis	Wooden decks and air-filled pontoons
Payload Items	Refrigerated food module	Refrigerated food module, snowmobiles, berthing module
Payload Weight, W_p (lb)	19,200	28,600
Tare Weight, W_t (lb)	19,500	12,500
Gross Weight, W (lb)	38,700	41,100
Payload Fraction, W_p/W	0.50	0.70
T_{air} (°C)	−23	−23
Max 1 min Start-up Resistance, $R_{1\text{-min}}$ (lb)	7400	5300
Start-up Duration to Steady-state (min)	8.0	0.8
Steady-State Resistance, R (lb)	6300	4700
$T = R + 3\sigma_R$ (lb)	7500	5100
Average Resistance Coefficient, R/W	0.16	0.11
Total Resistance Coefficient, T/W	0.19	0.12
Payload Efficiency, W_p/T	2.6	5.6

GrIT had more time to procure ARCS for its 2011 season, and we made several design revisions based on SPoT10-11 experience (Lever et al. 2011). Figure 18 shows the two ARCS deployed five months later during GrIT11. Conceptually similar to SPoT10-11 ARCS, these sleds used custom-made pontoons without plastic end caps. Six pontoons, filled to 1 psi, supported each 16 ft wide × 20 ft long wood-framed cargo deck on two 8 ft wide HMW-PE sheets. The decks used engineered lumber (9.5 in. deep I-joists skinned with 0.5 in. thick plywood) to increase strength and weight and included D-ring attachments to help transmit inertial forces at start-up.

Tare weight of the GrIT11 ARCS was 5000 lb (including a small ski-nose spreader). Pre-departure mobility tests with 23,000 lb of payload yielded $R/W = 0.11$ and a payload efficiency of $W_p/T \approx 6$ at an air temperature of −14°C. The measured resistance coefficient was about 40% higher than measured for GrIT10 dual-bladder sleds at the same air temperature. The short slider length of the ARCS relative to dual-bladder sleds (20 ft vs. 60 ft) and the short duration of the test segments (3–4 min between turns) could account for the higher ARCS towing resistance.

Figure 18. Prototype ARCS used during GrIT11 to transport cargo to Summit Station (*upper*) and during pre-departure tests (*lower*). Each wood-framed deck measured 16 ft wide × 20 ft long and was supported by six cylindrical air-filled pontoons (*red*) that served as a compliant suspension between the deck and two HMW-PE sheets (*white*) towed via a ski-nose spreader.

During the GrIT11 field campaign, the crew reported that the ARCS displayed excellent stability and ride quality. Importantly, both GrIT11 ARCS completed the Thule–Summit round trip with no pontoon failures although the pontoons leaked air through their seams at rates that required topping up every couple of days. One sled did experience a failure on the return leg: during a 360° turn, the edge of the HMW-PE sheet scooped snow under the pontoons, and the resulting wedging action split the side of the wooden deck (Figure 19). The crew was able to repair the deck, but the event demonstrated a need to control snow intrusion under and between the pontoons during travel and snowstorms.

Figure 19. GrIT11 cargo deck damage caused by snow intrusion under the pontoons during a 360° turn.

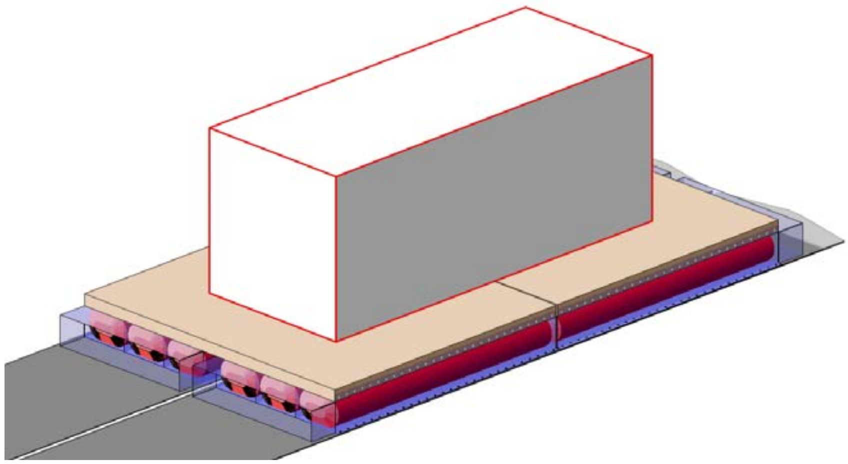
For GrIT11, we also generated an in-field solution to eliminate time-consuming daily crew-tent setup and removal: very lightweight ARCS that used spare pontoons and 2 × 4 wood-framed decks (Figure 20). These sleds weighed only 500 lb, towed very easily, were inexpensive to build, and slid on the pontoons themselves with no apparent abrasion problems. Their good performance suggests that ARCS technology could easily be adapted to meet the needs of lightweight science traverses in Antarctica and Greenland.

Figure 20. Very lightweight ARCS that slide on their pontoons, built to carry GrIT11 crew tents.

3.3 Tube-in-Pouch ARCS

Following GrIT11, we sought two major design revisions to ARCS: low-leakage pontoons and means to prevent snow intrusion. This resulted in the “tube-in-pouch” ARCS design where fabric pouches are bolted between the HMW-PE sheets and the cargo deck. These pouches form the structural connection, prevent snow intrusion, and allow cylindrical pontoons with no attachments to slide into individual pouch sleeves. Figure 21 shows the concept as intended to transport SPoT’s refrigerated food module during the 2011–12 season (Lever 2011b). We also designed smaller tube-in-pouch ARCS for the PIG traverse (Lever 2011c).

Figure 21. The tube-in-pouch ARCS concept to support SPoT's refrigerated food module. Each wooden deck measures 16 ft wide × 14 ft long and sits on six 24 in. diameter × 14 ft long single-chamber pontoons filled with air at 1 psi. The pontoons (*red*) slide into three-sleeve fabric pouches (*partially transparent blue*). The pouches have sealable dry-bag enclosures at each end to allow access to the fill valves and to swap pontoons if needed. Reinforced fabric along the pouch sides allows them to be bolted to the decks and to HMW-PE sheets by using battens to clamp them in place.



We conducted laboratory tests to help select low-leakage pontoons (Weale et al. 2011). We solicited 12 in. diameter sample pontoons from several vendors, including the supplier of GrIT11 pontoons, and subjected them to 5 in. cyclic compression tests at −40°C to simulate ARCS travel over polar sastrugi (Figure 22). The sample pontoon provided by Federal Fabrics-Fibers (FFF) performed the best, surviving 10,000 compression cycles with no air leakage. FFF commercially produces similar two-layer inflatable structural beams ("air beams") for U.S. Army rapidly deployable shelters. Based on our low-temperature compression tests, FFF was selected to supply pontoons for tube-in-pouch ARCS (Figure 23).

FFF also constructed the fabric pouches for SPoT11-12, PIG11-12, and GrIT12 tube-in-pouch ARCS (Figure 23, lower photo). They reviewed possible fabric options with us and selected a polyurethane-coated fabric with good low-temperature specifications based on the fabric-manufacturer's data.

Figure 22. Cyclic compression tests conducted at −40°C on a 12 in. diameter sample pontoon from FFF (Weale et al. 2011). Compression cycles were 5 in. stroke and 4 s periods. Sample pontoons were monitored for leaks during the tests by measuring air pressure.

Figure 23. Two-layer construction of a FFF sample pontoon (*upper*) mimicked that of the larger pontoons supplied for tube-in-pouch ARCS (*lower*): an impermeable liner (*clear*) resided within a tough, woven outer shell (*black*). The pouch material in 2011–12 was two-tone with a gray exterior and a tan interior.

SPoT chose not to construct and deploy its ARCS for 2011–12 owing to last-minute season-mission changes. However, the PIG traverse crew assembled and deployed four smaller ARCS, each consisting of 8 ft wide × 16 ft long wood-framed decks supported by four 18 in. diameter × 16 ft long pontoons in a single, four-sleeve pouch (Figure 24). These ARCS were sized to fit inside an LC130 aircraft and designed to carry 10,000 lb of payload each (Lever 2011c).

Figure 24. PIG11-12 ARCS loaded with 7000 lb of concrete blocks and 1000 lb of totes during mobility tests in October 2011.

We were able to conduct limited mobility tests of a PIG11-12 ARCS near McMurdo before it was flown to West Antarctica. A Tucker Sno-Cat towed the sled loaded with 8000 lb over 3–4 ft high snow bumps at 2–4 mph (Figure 25). Sled motion was very smooth and stable. Because we towed through a long strap rather than directly from the Tucker hitch, the steel tow plate dug into the snow, causing snow to pile onto the front of the sled. Despite this, snow did not wedge under the pouch. The side battens clamping the pouch to the HMW-PE sheet also worked well to prevent snow from intruding under the pouch during turns. Lateral motion of the sled was minimal, and no wear was apparent on the pouches.

We then connected the sled to a Case 530 Quadtrac with instrumented load pin to measure towing forces. The air temperature was –11.5°C, and the towing force averaged about 1000 lb. It was clear that gouging by the tow plate contributed significantly to the towing force (forces actually rose slightly during the test as snow built up on the nose). Nevertheless, the measured average corresponded to $R/W \approx 0.09$ based on a gross weight of 11,000 lb (8000 lb cargo + 2000 lb deck + 1000 lb sled and tow plate). This corresponds to a payload efficiency of $W_p/T \approx 8$. We would expect that towing with the tow plate raised (e.g., using a spreader) and having two decks in line on the same sled would significantly improve sled performance. Note that for a steel cargo sled, tare weight would be about 20,000 lb to carry the same 8000 lb payload, and payload efficiency would be only $W_p/T \approx 3$ for an optimistic $R/W \approx 0.1$.

Figure 25. Sequence of PIG11-12 ARCS towed over 3 ft snow bump near McMurdo. Snow buildup at the front of the sled resulted from towing with a strap rather than using a spreader or connecting directly to the tractor hitch.

The PIG11-12 ARCS performed very well throughout the field season, based on feedback from PIG crew. The sleds completed approximately 1700 miles of travel, much of it over soft snow and large sastrugi. The ARCS rode well and had no problems with snow intrusion, air leakage, or pouch material failure. PIG12-13 used the same ARCS with similarly successful results.

During 2012, GrIT deployed five tube-in-pouch ARCS based on the same design as SPoT11-12 and PIG11-12 ARCS (Lever 2011d). Each ARCS deck measured 15 ft 8 in. wide × 20 ft long and was fabricated from engineered lumber with minor revisions from GrIT11. The design payload weight was 25,000 lb for a tare weight of only 5000 lb (payload fraction W_P/W = 0.83). The main payloads for GrIT12 ARCS were two empty steel fuel tanks weighing 24,000 lb each (intended for fuel storage at Summit) and a 14,000 lb roller-packer to aid skiway grooming at Summit. Two ARCS also transported food, spare parts, and minor cargo inside Weatherport tents. Figure 26 shows the main group of four ARCS loaded for the outbound trip from Thule to Summit.

Figure 26. GrIT12 ARCS loaded for an outbound trip to Summit Station. The two front sleds carried two 24,000 lb empty steel fuel tanks. One rear sled carried a 14,000 lb roller-packer, while the other rear sled carried food and tools inside a tent. As with its bladder sleds, GrIT towed the assembly of four adjacent HMW-PE sheets through a ski-nose spreader bar.

GrIT12 crew reported good stability and ride quality of the ARCS along with no pontoon leaks. The only minor issue arose early: two pouches developed tears at their corners where they were bolted to the HMW-PE sheets (Figure 27). The crew installed diagonal straps (see Figure 29) to prevent further tearing, and the ARCS successfully completed their round trips with no further issues. GrIT12 delivered a total of 66,000 lb of cargo to Summit on ARCS.

Figure 27. A fabric tear along the rear corner of a GrIT12 pouch, outlined in *red*. The crew installed diagonal straps (see Fig. 29) to prevent further tearing at the pouch corners.

Pre-departure and field observations indicated that the GrIT12 pouch fabric stiffened noticeably at temperatures below about −20°C. CRREL subsequently conducted low-temperature flex-durability tests on this fabric and a selection of alternative fabrics (Lever et al. 2014b). These tests revealed that an alternate polyurethane-coated fabric was far more flexible and durable at −40°C. We recommended using this fabric for future SPoT, PIG, and GrIT ARCS pouches. We also recommended that SPoT install diagonal straps between the ARCS decks and HMW-PE sheets to prevent pouch tears.

For 2012, GrIT acquired a 7000 lb prefabricated module intended to support field science along the route. This well-insulated module included bunks for four people, a small kitchen, heat, and electrical power (generator, batteries, and solar panels). We again produced an in-field solution to transport it, reusing GrIT11 pontoons to support a 16 ft wide × 20 ft long wood-framed deck on two HMW-PE sheets (Figure 28). This lightweight

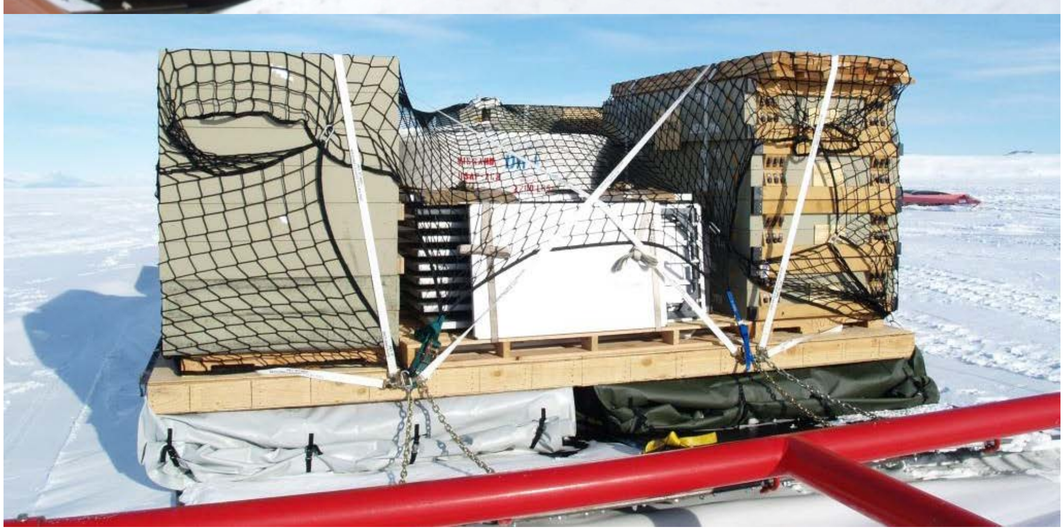
ARCS performed very well to support robotic ground-penetrating-radar (GPR) surveys along the GrIT route (Lever at al. 2013).

Figure 28. GrIT reused its 2011 pontoons to carry an 8 ft × 8 ft × 20 ft long prefabricated science-support module in 2012, here shown supporting robotic GPR surveys conducted along the route.

SPoT put its ARCS into service during the 2012–13 season to carry the tool shed and miscellaneous cargo on SPoT2 (Figure 29). SPoT2's season mission included staging equipment for the WISSARD science project. These ARCS performed very reliably with no air leakage from pontoons and no tearing of fabric pouches. Minor cracks did occur on some pouches, resulting from flexing at low temperatures. For 2014–15, SPoT acquired ARCS pouches constructed from the recommended low-temperature fabric (Lever et al. 2014b) to improve flex durability.

Unfortunately, the instrumented tractor on SPoT2 towed mixed sled trains in 2012–13: modules or containers on ISO ski kits, the tool shed on ARCS, and modules on a new ISO ski kit (ISO-2) developed for WISSARD and described in the next section. Consequently, we currently have no towing-resistance data for ARCS-only sled trains across Antarctica.

Figure 29. SPoT2 transported its tool shed (*upper*) and miscellaneous cargo (*lower*) on ARCS during the 2012–13 season. The ARCS performed very reliably. Note the diagonal yellow straps between the deck and the HMW-PE sheets (*upper*) to prevent pouch tearing.



3.4 ISO-2 cargo sleds for WISSARD

The WISSARD multi-year science project required staging ice-sheet drilling equipment, underwater vehicle deployment and recovery equipment, laboratories, and living facilities roughly 600 miles from McMurdo near the southern end of the Ross Ice Shelf. From the onset, USAP planned to mobilize, resupply, and demobilize WISSARD by traverse from McMurdo. Prefabricated modules, based mainly on ISO containers, would contain much of the needed equipment and facilities. In 2010, we examined the payload requirements and recommended against using the existing ISO ski kits owing to their high tare weight, towing resistance, and cost. Unfortunately, ARCS were an unproven alternative at that time. Instead, we helped USAP to redesign the steel ISO kits to reduce their weight, resistance, and cost. The following were the main design changes:

- Larger, lighter skis with flat bottoms (rather than V-shaped bottoms)
- Elliptical rather than circular ski noses
- Black rather than white HMW-PE sliding surfaces on the skis
- Non-steering ski trucks
- Ski trucks connected using the ISO container as the main structural element (connecting cables used only to tow the ski kit around without a container on top)
- No fore–aft travel in the ski trucks relative to the ISO container
- Towing cables rather than hard-hitch towing bars
- Rear personnel deck and ramp to improve safe access to container doors

Figure 30 shows the resulting ISO-2 ski kit prior to deployment, and Table 5 summarizes the changes in tare weight and ground pressure for the ISO-2 kits relative to the original ISO kits.

Figure 30. A rear view of an ISO-2 ski kit before deployment to Antarctica.

Table 5. Physical characteristics of the original ISO and ISO-2 ski kits, each carrying a 20,000 lb container. Here the entire container (including its empty weight) is considered payload. Ski contact lengths do not include circular- or elliptical-nose sections.

Parameter	Original ISO Kit	ISO-2 Kit
Tare Weight, W_t (lb)	19,500	14,000
Ski Contact Length (in.)	108	108
Ski Contact Width (in.)	36	42
Payload Weight, W_p (lb)	20,000	20,000
Ground Pressure (psi)	2.5	1.9
Payload Fraction, W_p/W	0.51	0.59
Tare Fraction, W_t/W	0.49	0.41

The V-shaped ski bottoms of the original ISO kits increased ground pressure and hence ski sinkage until the full ski-width engaged the snow. This sinkage also required that the ski trucks be steerable, which added the complexity and cost of turntables (flat bearing surfaces connected through a vertical pin) on the front and rear benches. Also, the circular ski noses tended to plow snow and accentuate porpoising motions (Lever et al. 2004). For the ISO-2 skis, we specified wider, flat-bottomed skis with beveled edges to side-slip the sleds during the gentle turns along the traverse route. This reduced ground pressure and eliminated the need for turntables on the benches. Also, as demonstrated for steel fuel sleds (Lever et al. 2006), elliptical noses reduce plowing at the front of the skis. Specifying black HMW-PE sliding surfaces aimed to increase solar gain from sunlight scattered upwards through the snow.

An intact, steel ISO container is a very stiff and strong structure. We felt it could easily provide the structural connection between the front and rear ski trucks and allow the ISO-2 kits to lock its benches directly to the ISO container. This eliminated the fore–aft slides in the original ISO kits and the roll motion between the benches and the container that was accommodated in the flex of the turntable pins (SPoT has broken or bent numerous turntable pins as a consequence). These changes also reduced complexity and weight. The switch to towing cables from hard-hitch towing bars also reduced weight. For rare occasions where the sleds must be moved backwards short distances, they can be towed rather than pushed rearward.

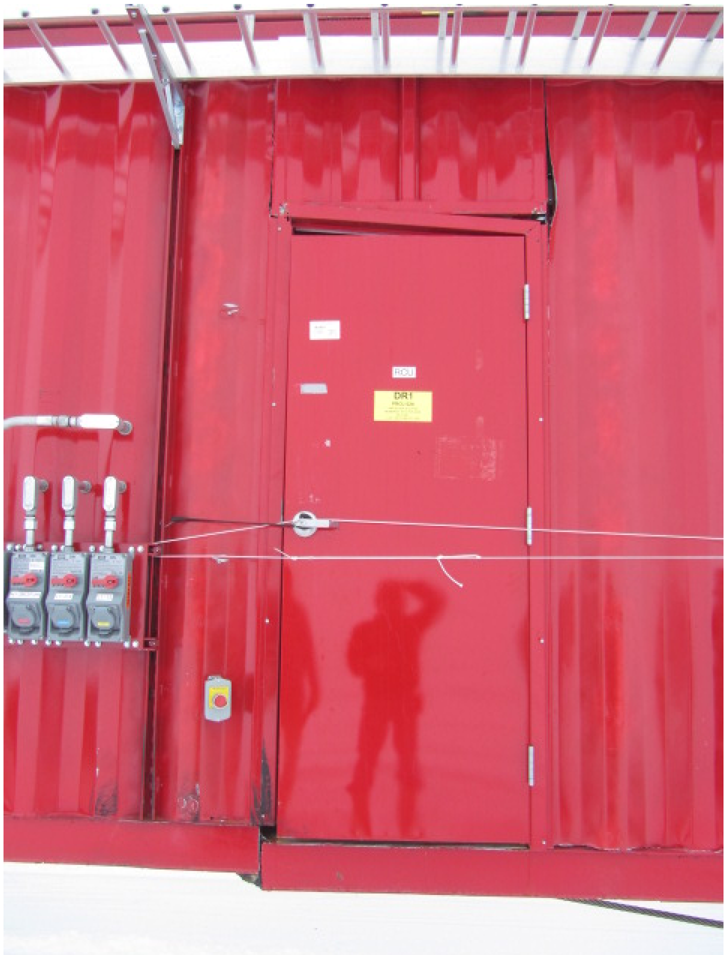
Cumulatively, these design changes reduced tare weight by 5500 lb (28%) per kit despite increasing ski contact area and improving access safety via rear decks. Simplifying the kits also reduced costs: the original ISO kits cost about $100,000 (2002) each whereas the ISO-2 kits averaged

$70,000. Although weight and cost reductions were not as significant as for bladder sleds and ARCS, this was a satisfying result.

SPoT2 towed several WISSARD containers on ISO-2 kits across the Ross Ice Shelf in 2012–13 (Figure 31). Sleds with essentially intact ISO containers performed well. Unfortunately, several WISSARD containers were heavily modified for use as laboratories and living spaces and thus had numerous cutouts for windows and doors. These cutouts caused stress concentrations, and the containers broke welds and cracked their steel skins in ways consistent with high shear stresses resulting from torsional loads (Figure 32). We share the blame for these failures, having not included torsional strength or load specifications for modified ISO containers intended for transport on the ISO-2 kits. We have since passed along these specifications. The container itself could be reinforced at cutouts to support the torsional loads, or torsion tubes could be attached between the front and rear ski trucks to carry the torsion-generated stresses. Note that the original ISO kits unintentionally reduced torsion-generated stresses on their containers by allowing several inches of roll motion to occur before the containers contacted the benches. As noted, the turntable pins flexed to accommodate this motion, which eventually led to bent and failed pins.

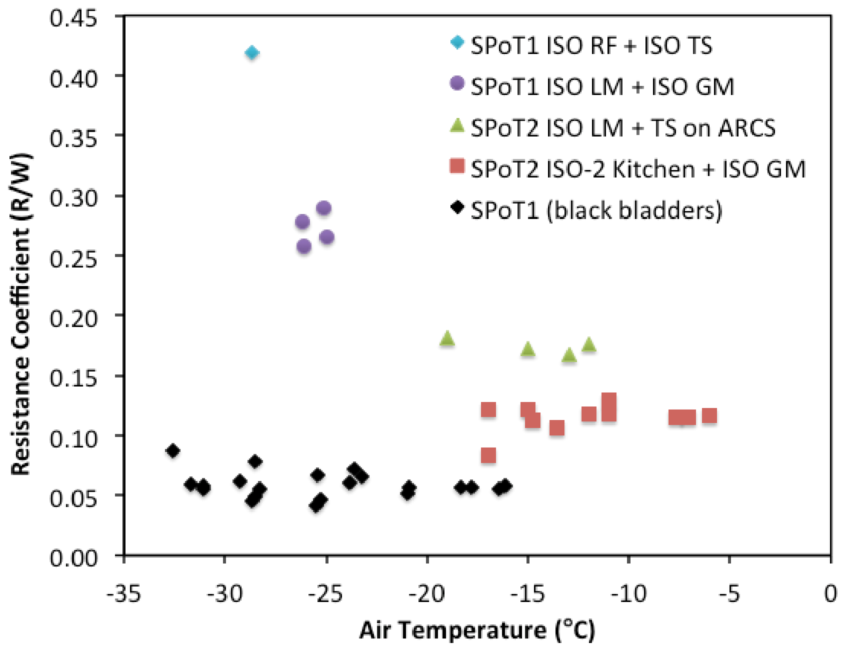
Figure 31. Two 40 ft long WISSARD containers on ISO-2 ski kits towed by SPoT2 across the Ross Ice Shelf in 2012–13. Note the shallow, flat-bottom ruts made by the skis relative to the towing tractor's deeper ruts seen under the container.

Figure 32. Cracks and deformation, resulting from torsional loads, in the WISSARD hot-water drill container on an ISO-2 kit. The door cutout weakened the container skin and likely caused stress concentrations to initiate the cracks.



The instrumented tractor on SPoT2 towed mixed sled trains of modules and containers on ISO and ISO-2 kits. As with the ARCS, we thus have no towing-resistance data solely for ISO-2 kits to compare their performance directly against the ISO kits. Nevertheless, we have compiled the mobility data from 2012–13 from both SPoT1 and SPoT2 for cargo-sled trains, and it does provide some insights (Figure 33).

Figure 33. In 2012–13, the SPoT1 instrumented tractor towed mainly black-bladder sleds. However, it briefly towed ISO-kit fleet-support sleds through the Polar Swamp near South Pole (RF = Refrigeration Module, TS = Tool Shed, LM = Living Module, GM = Generator Module). Also, the SPoT2 instrumented tractor staged a variety of WISSARD cargo sleds, consisting of ISO and ISO-2 ski kits and ARCS (Kitchen = Kitchen Module), on the Ross Ice Shelf. The resistance coefficients for these cargo-sled trains were all significantly higher than for black bladders towed by SPoT1 across all terrain in 2012–13.



As noted in Section 2.4, SPoT1 towed mainly black bladders of fuel in 2012–13 (see Figure 13 for resistance data). However, its fleet-support sleds were containers on ISO kits, and its instrumented tractor towed these sleds in the vicinity of South Pole. Figure 33 shows that the resistance coefficients for these ISO kits were 3–6 times higher than for black-bladder sleds at similar temperatures across the same snow conditions. For WISSARD, SPoT2's instrumented tractor towed a living module on an ISO kit together with a tool shed (container) on an ARCS. This combination performed much better but was still significantly worse than black bladders. It is possible that the ARCS provided most of the resistance reduction, but air temperatures were higher, and the range did not overlap with that of SPoT1 ISO sleds. SPoT2's data from a sled train of one ISO and one ISO-2 sled performed better still although again at temperatures much higher than SPoT1 ISO sleds. Snow strength also plays an important role for ISO and ISO-2 kits because their skis create ruts and hence develop snow-compaction resistance in addition to sliding friction.

The combination of cold, soft snow near South Pole creates the worst conditions for steel-ski cargo sleds and sled trains.

A further point about Figure 33 warrants mention: the plotted resistance per unit weight (R/W) includes tare weight. The payload fractions for bladders sleds and ARCS (including spreaders) are 0.93 and 0.83, respectively. By comparison, ISO and ISO-2 kits at their maximum payloads can achieve payload fractions of only 0.64 and 0.71, respectively. That is, when towing steel-ski cargo sleds, much of the tractor's effort is devoted to towing tare weight rather than payload weight, and resistance per unit weight is much higher. The loss in payload efficiency, which includes both effects, is dramatic. In the next section, we compare the payload efficiencies of each sled type for the demanding conditions encountered across the Polar Plateau.

4 Discussion and Conclusions

With NSF-PLR support, CRREL, SPoT, GrIT, PIG, and WISSARD personnel have collaborated to develop efficient, lightweight fuel and cargo sleds for polar traverses. The main impetus has been a need to reduce costs to resupply research stations and hence free up funding to support the scientific research that justifies these stations. A concerted effort to understand over-snow mobility through field investigations and engineering analyses has underpinned a rapid sled-development pace. These investigations have revealed the prominence of factors affecting sled–snow sliding friction and an overarching need to increase payload fraction by reducing tare weight. Also, regular interaction with traverse crews has been essential to ensuring that solutions are practical to implement and likely to be reliable under demanding field conditions.

To a large extent, we have succeeded in this effort. The performance of both fuel and cargo sleds has increased substantially as measured by the payload efficiency, or payload carried per unit towing force (W_p/T). Concurrently, sled capital costs have decreased. It is helpful to summarize the performance gains made to date although we must first provide a suitable basis for comparison.

Snow strength and sled–snow interface temperature both affect sled performance, which thus varies spatially and temporally during a traverse. Snow strength strongly influences the resistance of steel sleds owing to their higher contact pressures and consequent snow-compaction resistance. Sled–snow interface temperature, and hence sled thermal budget, strongly affects the sliding friction of both steel and lightweight, flexible sleds. The role of snow strength on sliding friction is not yet understood, but it probably affects the actual contact area that experiences frictional heating. These factors complicate performance comparisons between sleds.

We have compiled sled resistance per unit weight (R/W) as a function of air temperature to account partially for the role of sliding friction. Air temperature is a convenient surrogate for sled–snow interface temperature and reasonably collapses R/W for each sled type (Figures 9, 12, 13, 33). For SPoT, the lowest air temperatures normally occur across the Polar Plateau, which also includes a section of the softest snow along the route. This is the most demanding combination of environmental conditions. We may thus compare the performance of sleds in the interval −23°C to −33°C, which generally occurs on the Polar Plateau, to highlight the performance gains achieved through our development efforts. For convenience, we call this the sled performance at −28 ± 5°C.

Figures 9 and 13 show R/W for tan and black bladders at air temperatures of −28 ± 5°C. The average of these data is 0.096 for tan bladders and 0.056 for black bladders. Allowing for resistance variations ($T = R + 3\sigma_R$), the corresponding values of T/W are 0.137 and 0.080, respectively. Sled payload fraction is the same for both bladder colors, $W_p/W = 0.93$, including a standard four-sled spreader. The corresponding payload efficiencies (W_p/T) at −28 ± 5°C are thus 6.8 for tan bladders and 11.6 for black bladders. That is, for no cost penalty, black bladders offer a 70% performance gain over tan ones across the most demanding environmental conditions. This benefit derived directly from investigations into sled–snow sliding friction and the choice to use passive solar gain to warm the sled–snow interface.

The few data we have for steel fuel sleds at −28 ± 5°C in Antarctica and Greenland (Lever and Weale 2011) suggest that $R/W \approx 0.4$ and $T/W \approx 0.5$ are reasonable resistance estimates for that temperature interval. These values are also consistent with SPoT1 data for steel ISO sleds on the Polar Plateau (Figure 33). Accounting for payload fraction (0.63), we estimate a payload efficiency of $W_p/T \approx 1.3$ for steel fuel sleds at −28 ± 5°C. That is, black-bladder sleds have achieved a performance gain of about 10:1 under the most demanding conditions compared with the steel sleds they have replaced.

Unfortunately, we cannot as easily compare the performance of steel and lightweight cargo sleds. We have no resistance data for ARCS across the Polar Plateau. The few data for steel ISO kits at −28 ± 5°C suggest that $R/W \approx 0.4$ and $T/W \approx 0.5$ are reasonable averages (Figure 33). Payload fraction varies with the specific payload carried, but we may use 20,000 lb as a typical value to calculate a payload fraction of $W_p/W = 0.51$. Thus, we may estimate the payload efficiency of the original ISO kits as $W_p/T \approx 1.0$ at −28 ± 5°C, which is slightly worse than for steel fuel sleds.

ISO-2 kits are likely to improve payload efficiency compared with ISO kits through their combination of higher payload fraction (0.59) and lower resistance per unit weight resulting from lower ground pressure. The limited performance data from WISSARD (Figure 33) are encouraging but inconclusive owing to higher air temperatures and mixed sled trains. Despite being an improvement on ISO kits, the steel skis on ISO-2 kits conduct away frictional heat, and the kits are heavier than ARCS for the same payload capability. We therefore do not expect ISO-2 kits to be a better long-term option than ARCS to transport rigid cargo and fleet-support modules efficiently at −28 ± 5°C.

Our only data from a head-to-head comparison of an ISO kit with an ARCS was on firmer snow and at slightly higher temperatures (−23°C) near McMurdo (Table 2). The results were encouraging with payload efficiency more than doubling from 2.6 to 5.6 owing to the ARCS higher payload fraction (0.70) and lower resistance per unit weight. GrIT's tube-in-pouch ARCS have an even higher payload fraction (0.80–0.83), and we expect the R/W of ARCS eventually to approach that of bladder sleds because of their similar compliant, low-pressure contact with snow. If we can achieve this through design optimization, the payload-efficiency advantage of ARCS over steel cargo sleds (including ISO-2 kits) should also approach 10:1 over the cold, soft snow of the Polar Plateau.

In addition to this significant efficiency advantage, ARCS provide other performance advantages compared with steel cargo sleds. Their flat decks and compliant suspensions produce a very gentle ride over rough snow and permit easy grouping of sleds to accommodate large loads (for example, the 40 ft long steel tanks transported to Summit Station by GrIT12, Figure 26). Groups of ARCS should be well suited to carrying large, prefabricated facilities or large pieces of sensitive science cargo. ARCS should thus be able to capitalize on assembly labor costs savings relative to airlift delivery in addition to cost-per-pound savings (Lever and Thur 2014).

Importantly, lightweight, flexible sleds are also less expensive to buy than corresponding steel sleds. Each 3000 gal. steel fuel-tank sled cost $102,000 when last purchased in 2007. Each 3000 gal. bladder sled unit currently costs $16,000. Similarly, the original ISO kits cost about $100,000 (2002), ISO-2 kits cost about $70,000 (2012–13), and ARCS currently cost about $30,000 each, all with about 25,000 lb of payload capacity. That is, both performance gains and cost reductions have been possible through the introduction of lightweight materials and improved understanding of over-snow mobility.

We have experienced some reliability and durability issues with both bladder sleds and ARCS. This is unsurprising given the rapid evolution and adoption of sleds that use plastic sheets and polymer-coated fabrics at temperatures much lower than their customary applications. However, we are aggressively evaluating material and handling options to maximize sled durability (Lever et al. 2014b; Weale et al. 2015). These efforts have already led to greater sled durability, and we expect the usable life of flexible sleds will be long enough (5–10 years) that they will present much higher performance for lower life-cycle costs compared with steel sleds.

Black-bladder sleds are now a proven, high-performance technology, and we anticipate no changes in their design for the near future. However, the data here suggest that SPoT1 could depart McMurdo with ten bladders per tractor rather than eight and still achieve reliable mobility performance and low round-trip times. Similarly, SPoT2, traveling over SPoT1's compacted trail, could reliably boost its per-tractor bladder count to 12–16 across the Ross Ice Shelf, which would open options to shuttle bladders from the base of the Leverett Glacier to South Pole as a means to increase throughput, and hence payback, of the two fleets. Indeed, by necessity, a SPoT2 tractor reliably towed groups of 12–16 mostly tan bladders across the Ross Ice Shelf in 2011–12 (Figure 12). Groups of 12–16 black bladders will tow even easier.

ARCS are more complex systems than bladder sleds, and their development is still underway. However, they potentially can provide a broader range of capabilities and thus offer broader and complementary benefits. Groups of ARCS have already demonstrated the ability to transport oversize cargo, and this capability offers cost savings through stateside prefabrication that would extend benefits beyond cost-per-pound savings. Also, both SPoT fleets would benefit from using ARCS rather than ISO kits to carry their fleet-support modules. This would free-up tractor towing capacity to add fuel or cargo payload through additional bladder sleds or ARCS. Small but worthwhile efficiency gains could derive by designing prefabricated, composite decks with tow-through capability to eliminate the need to tow ARCS via spreaders and to permit more versatile sled-train arrangements. Such decks could also offer greater durability, and hence lower life-cycle costs, compared with wood-framed decks. Also, as demonstrated by PIG (Figures 24 and 25) and GrIT (Figures 20 and 28), we may apply ARCS technology to improve the efficiency and reduce costs for light science traverses across Antarctica and Greenland.

We are aggressively seeking to improve our understanding and modeling of sled–snow sliding friction, the dominant source of towing resistance for lightweight, flexible sleds. Within the next few years, we expect to optimize ARCS to achieve mobility performance similar to that of bladder sleds. Concurrently, we are gaining experience with durability issues and performance specifications needed to extend the useful lives of the constituent materials in bladder sleds and ARCS. Collectively, these efforts should complete the transformation of polar resupply traverses from heavy steel sleds to efficient, lightweight, flexible sleds.

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14. ABSTRACT
This report discusses the recent advances in the performance of sleds developed for polar resupply traverses. Researchers at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) have guided developments by using field mobility measurements that routinely included sled-train towing force, speed, and air temperature. Owing to its dominant contribution to towing resistance, researchers have made special efforts to understand the processes and design choices that affect sled–snow sliding friction. As a result, polar traverses now tow lightweight, flexible sleds that achieve significant performance and cost advantages relative to steel sleds. With an emphasis on Antarctic traverses, this report summarizes sled developments, performance data, insights, and future goals for sled technology.

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