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Greenland Inland Traverse (GrIT)

2010 Mobility Performance and Implications

James .H. Lever

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Final report

Prepared for National Science Foundation Office of Polar Programs
Washington, DC

Abstract: The National Science Foundation initiated the Greenland Inland Traverse (GrIT) to resupply science stations at NEEM and Summit via over-snow transport. The inaugural traverse in 2008, while successful, encountered mobility problems owing to steep slopes along the first 60 miles, soft snow along much of the route, and higher than expected towing resistance of the fuel sleds. With our guidance, GrIT implemented several changes to improve performance in 2010, and these changes were largely successful. Planned half-load shuttling reduced immobilizations on steep sections, omission of the steel fuel sled eliminated the worst-performing sled, and towing the fuel bladders two inline on long plastic sheets rather singly on separate sheets improved performance of the remaining fuel sleds. In addition, we instrumented the bladder sleds to quantify the expected dependence of towing resistance on sled-snow interface temperature. Sliding friction warms the sled and produces a thin meltwater layer that decreases towing resistance over cold snow. Furthermore, to assess benefits of artificially warming the sleds, one dual-bladder sled included electric heating blankets (optionally on or off) and the other included black wrappers to increase solar gain. This report summarizes GrIT10 performance, evaluates the changes implemented and assesses implications for future GrIT operations.

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Preface

The work was performed by Dr. James H. Lever of the Force Projection and Sustainment Branch, James S. Buska, Chief; Research and Engineering Division, Dr. Justin B. Berman, Chief; U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). The Deputy Director of ERDC-CRREL was Dr. Lance D. Hansen and the Director was Dr. Robert E. Davis.

The 2010 Greenland Inland Traverse would not have been possible without the dedicated commitment of its field crew and pre-deployment team: Brad Johnson, Robin Davies, Willow Fitzgerald, Zoe Courville, Kevin Emery, Jen Mercer, Allan Delaney, Erik Nichols, Allen Cornelison, Larry Levin, Jay Burnside, Dave Wantuch, Kim Derry, Maggie Knuth, and Thomas Kaempfer. These folks make it a pleasure to participate in GrIT. The author also gratefully acknowledges the support of Pat Haggerty and Renee Crain at NSF/OPP-ARC to establish and improve GrIT, and that of CRREL colleagues Jason Weale, Renee Melendy, Doug Punt, Nate Lamie, and Gordon Gooch for their help to mobilize these mobility studies. The author particularly wishes to thank Dave Wantuch for his field help and efforts to process the mobility data, and Robin Davies for his high-quality field notes and Rammsonde data after the author's departure.

COL Kevin J. Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

Executive Summary

The National Science Foundation Office of Polar Programs has implemented an over-snow traverse to resupply science stations at NEEM and Summit on the Greenland ice sheet from Thule Air Base. In 2008, the inaugural 705-mile Greenland Inland Traverse (GrIT) successfully demonstrated this mode of resupply. However, mobility problems reduced GrIT08's season performance: a) steep slopes along the approximately 60-mile transition onto the main ice sheet caused frequent immobilizations and unplanned shuttling of sled trains, b) soft snow along much of the route increased tractor sinkage and self-propulsion effort, and c) towing resistance, especially for the steel tank sled, was significantly higher than expected. Consequently, GrIT implemented several changes to improve performance for its 2010 traverse:

- Planned half-load shuttling through the transition.
- Wider tracks on the Case Quadtrac towing tractor to reduce ground pressure.
- An eastward route deviation from NEEM to Summit to travel over a lower accumulation of snow.
- Elimination of the steel fuel-tank sled.
- Longer high molecular-weight polyethylene (HMW-PE) sleds with two 3000-gal. fuel bladders inline rather than one.
- Trial of active and passive heating to warm the bladder sleds.
- A new spreader bar.
- Trial of a semi-rigid plastic cargo deck (Dura-Base).

GrIT10 reestablished a safe route through the crevasse-strewn transition and onto the main ice sheet. Planned shuttling of half-loads was very effective: it reduced immobilizations on steep slopes to just two and cut travel time to flat terrain from 9 days to 6 days.

Season performance was also much better in 2010. The Case towed higher gross weight into NEEM without shuttling and with no immobilizations. It hauled all heavy sleds as a single train outbound from NEEM and experienced only one immobilization en route to Summit. Although transit time from NEEM to Summit was 1 day longer than in 2008, the Case arrived towing 109,000 lb versus 63,500 lb, and the crew devoted about 2

hours each day to NSF-funded snow-science experiments. GrIT's delivered payload increased from 33,500 lb in 2008 to 175,100 lb in 2010, in large part through delivery to Summit of the Case and Tucker tractors.

Case drawbar capacity averaged DBP = 21,600 ± 1500 lb or DBP/W = 0.32 ± 0.02, essentially unchanged from 2008. Higher tractor weight probably offset expected benefits from wider tracks. Measured snow strengths were substantially higher in 2010, which could account for some fleet-performance improvement. It is not clear whether the eastward route deviation or seasonal weather differences account for higher strengths for approximately 200 miles outbound from NEEM, but fleet performance was certainly better and the extra route length (29 miles) amounted to less than 1 travel day.

Towing resistance of the heavy sleds substantially improved in 2010. After mile 78, the Case towed all heavy sleds as a single train at average resistance per unit weight T/W = 0.10 ± 0.01 and broke traction only once. This compares very well against GrIT08, where shuttling of half loads was frequently necessary. In 2008, trains consisting of HMW-PE bladder and cargo sleds averaged T/W = 0.13 ± 0.04 over the whole route and T/W = 0.16 ± 0.01 after NEEM, tank–cargo sled trains averaged T/W = 0.26 ± 0.04, and the steel tank developed T/W = 0.41 ± 0.08. Daily fueling was easily accomplished from fuel bladders in 2010, so fleet performance certainly benefited by omitting the steel tank sled.

Significant performance improvement also resulted from changes to the fuel-bladder sleds. We guided these changes with a better understanding of the role of sled–interface temperature on snow–sled sliding friction, the dominant resistance source for bladder sleds. The GrIT10 bladder sleds included instruments to quantify this resistance-temperature dependence.

The two GrIT10 bladder sleds each consisted of two 3000-gal. fuel bladders inline on single sheets of HMW-PE, compared with four similar bladders on four separate sheets in 2008. Longer sleds allow for longer-duration frictional heating over the snow, which in turn produces thicker meltwater layers to reduce sliding resistance. We also configured the bladder sleds to assess the benefits, if any, of active heating versus passive solar gain to increase sled–snow interface temperature and thereby reduce sled resistance. Sled1 used insulated heating blankets between the bladders and the sled to test two configurations: heaters on, heaters off (insulation only). Sled2 had thin, black-rubber covers over the bladders to increase solar gain.

Some performance improvement resulted from longer sled length. Average interface temperatures were 1–2°C higher under the second bladder on either sled, suggesting lower net resistance for dual-bladder sleds compared with GrIT08 single-bladder sleds. The GrIT10 sleds probably also ran warmer than those in 2008 owing to the presence of the heating blankets and the black covers. Average bladder–sled towing resistance correlated well with average sled–interface temperature, regardless of method to make the sled warmer (active heating, insulation, or solar gain). Sled resistance decreased with increasing interface temperature until approximately −5°C; higher interface temperatures produced no additional benefit.

Interestingly, for a given air temperature, GrIT10 bladder sleds developed more resistance than similar South Pole Traverse (SPoT) sleds. We are investigating whether cloudier conditions or softer snow account for this difference. Luckily, Greenland air temperatures are generally higher than Antarctic ones during their respective traverse seasons, so seasonal load limits based on maximum sled-train resistance end up being similar in both locations.

Compared with black covers, the resistance benefits from the heating blankets were small and limited to air temperatures below −10°C, namely 10–15% benefit with the heaters on and 0–5% benefit with the heaters off (insulation only). For air temperatures higher than −10°C, the heating blankets, whether on or off, generally performed slightly worse than the black covers. At present, the minor benefits of heating blankets at lower temperatures do not appear to justify their cost and operational complexity compared with black covers. Use of more thermally efficient black bladders would likely eliminate this small benefit in any event.

The new spreader bar performed well during GrIT10. It is easier to use, lighter weight, and less expensive than the triangular spreaders used in 2008. The design now includes a smoother nose shape and is sufficiently easy to build that the crew built a short version in Thule, using local materials, to help with half-load shuttling through the transition.

The Dura-Base cargo sled was an operational success. It was easy to assemble and load, and it stayed intact throughout the traverse to Summit. Cargo rode nicely on the sled and required little re-strapping, a big improvement from the slip–sliding behavior of cargo transported directly on HMW-PE sleds during GrIT08. Unfortunately, the resistance coefficient of the Dura-Base sled was substantially higher than that of the bladder sleds across all conditions, and resistance per unit weight of payload was essentially twice higher. This underscores the need to continue a GrIT–SPoT–CRREL effort to develop efficient, lightweight cargo sleds. GrIT11 will trial two air-pillow cargo sleds as part of this effort.

Lever and Weale (2009) examined the long-term economic feasibility of GrIT to resupply NEEM and Summit via overland traverse compared with the status-quo of LC130 aircraft resupply. Analyzing a single-swing, two-towing-tractor scenario, the authors concluded that the critical route segment is from just past the transition to NEEM, where 2008 mobility was about 7 bladders per Case Quadtrac and a per-Case performance of 8–10 is needed to break even.

GrIT10 achieved the needed performance. Analyses based on average sled-train resistance and temperature-dependent bladder–sled resistance confirm that the Case in 2010 trim can tow eight bladders (four dual-bladder sleds) with substantial reserve capacity. A performance of 10 bladders per Case is within reach by using black bladders, rather than less efficient black covers, to increase solar gain at low air temperatures. Interestingly, GrIT's 8–10 bladder tractor capacity is identical to the current load limit for SPoT. Warmer weather in Greenland compensates for weaker snow conditions to yield the same seasonal load limits.

GrIT11 will use two lighter Case Quadtracs with the same 485-hp engines and 36-in.-wide tracks as the GrIT10 Case. Ground pressure will be lower, which should significantly decrease rut depths and self-propulsion resistance. As with sled improvements, this benefit can be self-reinforcing: the tractors should develop more drawbar power, which allows higher towing speeds, which increases frictional heating, which lowers sled resistance. However, lower tractor weight could reduce maximum drawbar pull. Thus, the GrIT11 tractors should be monitored to determine whether lower ground pressure or higher weight provides optimum towing capacity for Greenland snow conditions.

We make the following recommendations for GrIT based on this work:

- Acquire black fuel bladders to increase passive solar heating and thereby reduce bladder-sled towing resistance. This will increase load limits or create reserve tractor capacity.
- Set the GrIT11 load limit equivalent to seven bladders per Case Quadtrac (six 3000-gal fuel bladders and a new air-pillow cargo sled on four sheets of HMW-PE). This limit recognizes that the GrIT11 Quadtracs are lighter than their GrIT10 counterpart and the air-pillow cargo sled is untested.
- Set the GrIT11 Case Magnum load limit equivalent to five fuel bladders.
- Install automated mobility instrumentation in the GrIT11 tractors to help assess season performance of the new tractors and sleds. Complement the mobility data with crew-acquired Rammsonde snow-strength profiles and field notes along the route.
- Plan to shuttle half-loads up the 60-mile transition onto the main ice sheet. This strategy worked well during 2010 to reduce frustrating and time-consuming immobilizations.
- Use the 2010 route alignment in 2011 for outbound travel from NEEM to Summit and the 2008 route alignment for return travel Summit to NEEM. Conduct Rammsonde profiles along both routes and compare snow-strength and mobility data to assess whether 2010 alignment offers better fleet mobility.
- Assess the performance of the lighter GrIT11 Quadtracs to determine whether lower ground pressure or higher weight optimizes towing capacity for Greenland conditions.

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
pounds (mass)	0.45359237	kilograms
pounds (mass) per square foot (psi)	4.882428	kilograms per square meter
quarts (U.S. liquid)	9.463529 E-04	cubic meters

1 Introduction

The National Science Foundation Office of Polar Programs (NSF-OPP) operates year-round research stations on the ice sheets of Antarctica and Greenland. Until 2006, these stations were resupplied entirely via ski-equipped LC-130 aircraft. The South Pole Traverse (SPoT) now partially resupplies South Pole Station from McMurdo Station, a distance of 1030 miles, using large, rubber-track tractors to haul fuel and cargo over the snow on flexible plastic sleds (Fig. 1). CRREL assisted SPoT development with route selection and sled innovations to improve fleet mobility (Lever et al. 2004, 2006; Weale and Lever 2008).

Figure 1. Two SPoT09-10 tractors setup each to haul eight 3000-gal. fuel bladders on four flexible plastic sleds 1030 miles from McMurdo to South Pole.

In 2008, NSF-OPP initiated the Greenland Inland Traverse (GrIT) to develop a similar capability to resupply Summit Station, at the height of the Greenland ice sheet, from Thule Air Base (Fig. 2). CRREL assisted with route selection, sled technology transfer, and overall feasibility assessment (Lever and Weale 2008). During its inaugural season, GrIT08 proved a safe route onto the ice sheet and delivered fuel to NEEM (a Danish–U.S. ice-coring camp) and Summit before returning safely to Thule. One-way route length was 705 miles.

The primary GrIT08 tractor was a Case STX 485 Quadtrac. It towed four 3000-gal. fuel bladders and some rigid cargo on flexible sheets of high molecular weight polyethylene (HMW-PE). The full heavy-sled train also towed a 3000-gal steel fuel-tank sled obtained from SPoT for daily refueling (Fig. 3). GrIT08 was first to use extruded HMW-PE sheets for flexible sleds; SPoT subsequently adopted this material to replace its welded sheets of ultra-high molecular weight polyethylene (UHMW-PE). The GrIT08 bladder sleds were similar to those used during SPoT08–09, except that each HMW-PE sled was half the length and carried a single bladder instead of two inline. GrIT08 also included a Tucker SnoCat towing fleet-support sleds.

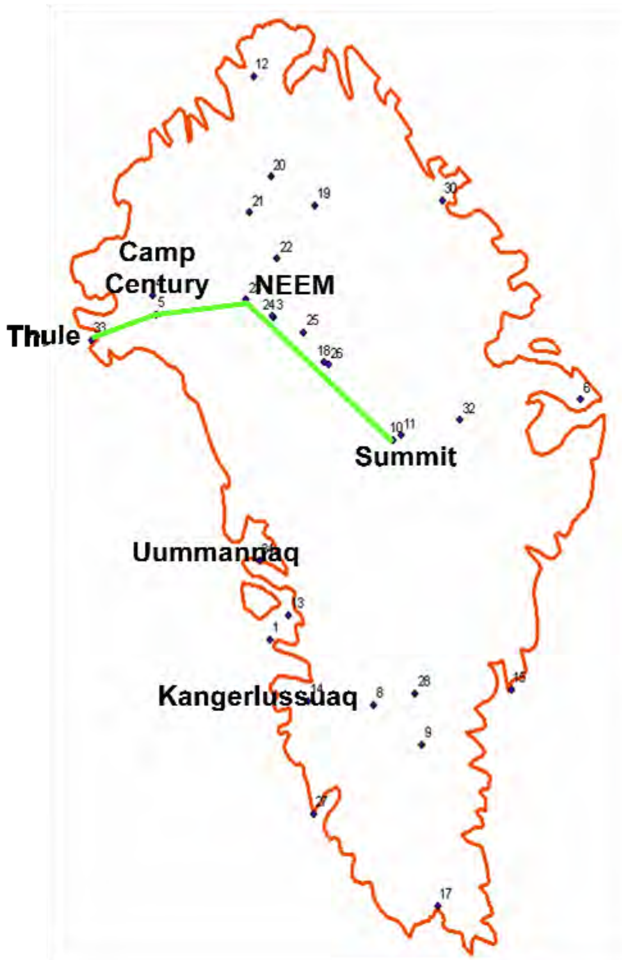

Figure 2. 705-mile GrIT08 route across the Greenland ice sheet. The transition onto the main ice sheet covered ~ 60 miles (about half the distance to Camp Century) and included numerous deviations to avoid crevasses. The 570 miles from Camp Century through NEEM to Summit Station had negligible slopes but consisted of soft snow.

Figure 3. Case Quadtrac towing all GrIT08 heavy sleds: a steel fuel tank, two flexible cargo sleds on a spreader bar and four flexible bladder sleds on a spreader bar. Note high sinkage of the Case rear tracks (~ 12 in.) owing to soft snow and high towing resistance.

Mobility of the Case heavy-sled train was significantly worse for GrIT08 than expected, based on SPoT experience. There were three main factors (Lever and Weale 2009): a) numerous steep slopes along the approximately 60-mile transition onto the main ice sheet caused frequent immobilizations and unplanned shuttling of half loads, b) soft snow along much of the route increased tractor sinkage and self-propulsion effort, and c) sled towing resistance, especially for the steel tank sled, was significantly higher than expected. Consequently, GrIT implemented several changes to improve performance for its 2010 traverse:

- Planned half-load shuttling through the transition.
- Wider tracks on the Case Quadtrac to reduce ground pressure.
- An eastward route deviation from NEEM to Summit to travel over lower accumulation snow.
- Elimination of the steel fuel-tank sled.
- Longer HMW-PE sleds with two 3000-gal fuel bladders inline rather than one.
- Trial of active and passive heating to warm the bladder sleds.
- A new spreader bar.
- Trial of a semi-rigid plastic cargo deck (Dura-Base).

The GrIT10 bladder-sled changes reflected recent insight gained from SPoT09-10 experience and analogy with ski-snow friction: over cold snow, sled towing resistance decreases significantly as sled–snow interface temperature increases (Colbeck 1992; Bäurle et al. 2007; Kaempfer and Lever 2009; Lever 2009). On snow with a temperature lower than about −5°C, dry snow grains produce high interface friction, with friction coefficient μ

~ 0.3. As the sled slides over the snow, frictional heating warms the snow–grain contact points and produces local melting. The sled also warms up in response. The resulting meltwater lubricates the sled–snow interface and reduces friction. The longer the sled, the longer the contact time is for frictional heating and the greater the effect of friction heating at reducing local interface friction. This process can produce too much meltwater and increase friction (via suction) when snow temperature exceeds about −5°C, but for most polar conditions, warmer sleds will slide easier than colder ones. Because the GrIT and SPoT bladder sleds produce so little snow deformation, snow-compaction resistance is small, and sliding friction governs their towing resistance.

Based on this understanding and preliminary model results (Kaempfer and Lever 2009), we expected that sleds with two bladders inline, as per SPoT practice, would have less resistance per unit weight than the single bladder sleds of GrIT08. Furthermore, the entire sled heat budget influences sled–snow interface temperatures, so active heating of the sled and passive heating of the bladders via solar gain should also reduce sliding friction. We implemented these changes for GrIT10 to quantify their benefits and assess their practical implications.

Lever and Weale (2009) conducted a comprehensive feasibility study of GrIT to assess the merits of traversing cargo to NEEM and Summit compared with conventional LC130 aircraft resupply. They concluded that a three-tractor GrIT fleet (two Case towing tractors and a Tucker support vehicle) would break even economically with a modest improvement in outbound towing capacity per tractor, from the equivalent of 7 fuel bladders achieved in 2008 to 8–10 fuel bladders. This improvement seemed achievable with a modest development effort. Other important factors, such as low emissions, reduced fuel consumption, out-size cargo capability, science opportunities along the route, and hedge against LC130 cost increases, also make GrIT an attractive alternative to aircraft resupply in Greenland.

Overall, the GrIT10 season objectives were to reestablish a safe route onto the ice sheet, deliver fuel to NEEM and Summit, deliver the Case and Tucker tractors to Summit as payload, and document fleet mobility performance in light of the equipment and route changes undertaken. This report summarizes GrIT10 mobility performance, evaluates the implemented changes, and assesses the implications for future traverse resupply operations in Greenland.

2 GrIT10 Tractors, Sleds, and Route Deviation

The GrIT10 fleet consisted of the same two tractors as 2008, both intended for delivery to Summit as payload. The Tucker SnoCat again towed fleet-support sleds that now included a 3000-gal. bladder sled for daily fueling, in lieu of the steel tank, and two spare 34-ft-long HMW-PE sleds from 2008 (Fig. 4). The Tucker is a 140-hp, four-track-drive tractor with articulated steering, and weighs 14,600 lb with average ground pressure of 1.8 psi. Mobility tests near Thule in 2009 (Lever and Weale 2009) indicated that it could reliably tow the 2010 sled-train weight (37,000 lb max.) on level snow.

The Case Quadtrac, a 485-hp four-track-drive tractor with articulated steering, weighed 69,500 lb in 2010 trim (with blade, crane, fuel, and operator). It was equipped with 36-in.-wide tracks (versus 30-in. tracks in 2008) and produced average ground pressure of 6.6 psi with 55% front, 45% rear weight distribution. The Case was thus "well balanced" based on manufacturer recommendations and results of the 2009 mobility tests (Lever and Weale 2009). Its full load consisted of four 3000-gal. fuel bladders on two 68-ft-long HMW-PE sleds plus the Dura-Base cargo sled (Fig. 5). It towed these sleds through a new 33-ft-wide ski-nose spreader developed specifically for GrIT.

Figure 4. Sled train behind Tucker SnoCat in 2010 (right to left): wannigan, orange sled with camp supplies, 3000-gal. bladder sled, short spreader, spare HMW-PE sled carrying outhouse, and snowmobile (photo courtesy Robin Davies).

Figure 5. Case Quadrac towing full load of dual-3000-gal. bladder sleds on either side of a Dura-Base cargo sled. The left-side bladder sled included electric blankets under both bladders, while both bladders on the right-side sled were wrapped in black covers. The photo (courtesy Robin Davies) shows Go North dogs and sleds catching a lift en route to NEEM.

We configured and instrumented the bladder sleds to quantify the effect of higher interface temperatures on towing resistance along the entire route. Each bladder sled measured 8-ft-wide × 68-ft-long × ½-in.-thick. We installed thermocouples (accuracy ± 0.1°C) along the length of the sleds, flush with the bottom surfaces (Fig. 6). In addition, we installed thermocouples to measure fuel temperature inside each bladder and air temperature over each sled. Radiometers also measured solar irradiance (W/m^2 on a horizontal surface) arriving at each sled, load shackles measured the towing resistance of each sled directly at the spreader bar, and GPS receivers measured sled position, speed, and altitude. Dataloggers on each sled recorded these data, sampled at once per second, and stored as 10-s averages.

The left-hand bladder sled (Fig. 5), designated Sled1, had two electric heating blankets installed under each bladder. These commercially available, flexible blankets had insulated backs, durable covers, and produced 1750 W each over 5- × 11-ft contact area (~ 340 W/m^2). A 15-kW generator installed on the Dura-Base cargo sled powered the heaters.

Figure 6. Thermocouples (23 per bladder) installed along the length of each bladder sled. Thermocouple sensing junctions were flush with the bottom surfaces of the sleds. Air temperature, bladder fuel temperatures and solar irradiance were also measured.

The right-hand bladder sled (Fig. 5), designated Sled2, had black-rubber covers (EPDM roofing material) wrapped over each bladder. The covers measured 20-ft-long × 15-ft-wide × 0.045-in.-thick and were tucked under the bladders before filling to achieve a tight fit.

We designed and trialed a ski-nose spreader bar in 2009, and GrIT10 team member E. Nichols modified its nose to improve its entry angle (Fig. 7). It consisted of 33-ft-long square-section steel tubing with ½-in.-thick HMW-PE bolted top, bottom, and at the nose. Four D-rings were available to connect the sleds, and two steel cables connected the spreader to the Case at its hitch pin. This design eliminated the skis and their attendant ruts present on the SPoT-derived 2008 spreaders in an effort to reduce towing resistance. To facilitate separate shuttling of the bladder sleds and the Dura-Base cargo sled, the GrIT10 crew built a shorter (16 ft) version of a ski-nose spreader with materials available in Thule (Fig. 8).

GrIT08 carried rigid cargo directly on HMW-PE sleds. This worked well in lieu of steel sleds, but their slippery surfaces and continuous flexing necessitated frequent repositioning and re-strapping of the cargo. GrIT team member L. Lavin suggested using Dura-Base mats as a semi-rigid cargo sled, and GrIT10 trialed this concept. Dura-Base mats are used to create expedient working surfaces for heavy equipment on soft terrain, including Arctic tundra. Each mat consists of 8-in.-thick molded and filled polyethylene, weighs about 1100 lb (with connectors) and has surface dimensions of 7 × 13 ft. The GrIT10 cargo sled consisted of eight interlocked mats measuring 14-ft wide × 52-ft long (Fig. 9). The mats were procured with top surfaces retaining their raised anti-skid elements and the bottom surfaces machined flat. Initial cargo load consisted of two filled 1500-gal. fuel bladders (~ 20,000 lb) and approximately 21,000 lb of rigid cargo (Fig. 10). The Dura-Base was towed directly on the snow from the Thule transition to NEEM. After off-loading the fuel, the crew slid it onto two adjacent 34-ft-long HMW-PE sleds to compare towing resistance in both configurations.

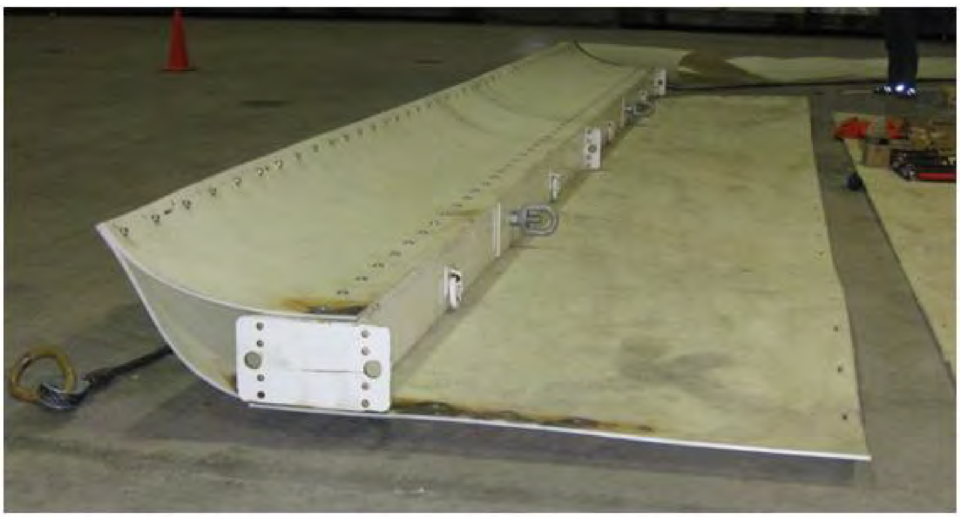

Figure 7. Ski-nose spreader bar for connecting the full sled load (two dual-bladder sleds and Dura-Base cargo sled) to the Case.

Figure 8. Smaller (16-ft-wide) spreader bar used to shuttle the two bladder sleds through the transition.

Figure 9. Assembled Dura-Base cargo sled, consisting of eight interconnected tan mats, connected to the large spreader (via lifting straps) and loaded for a test run.

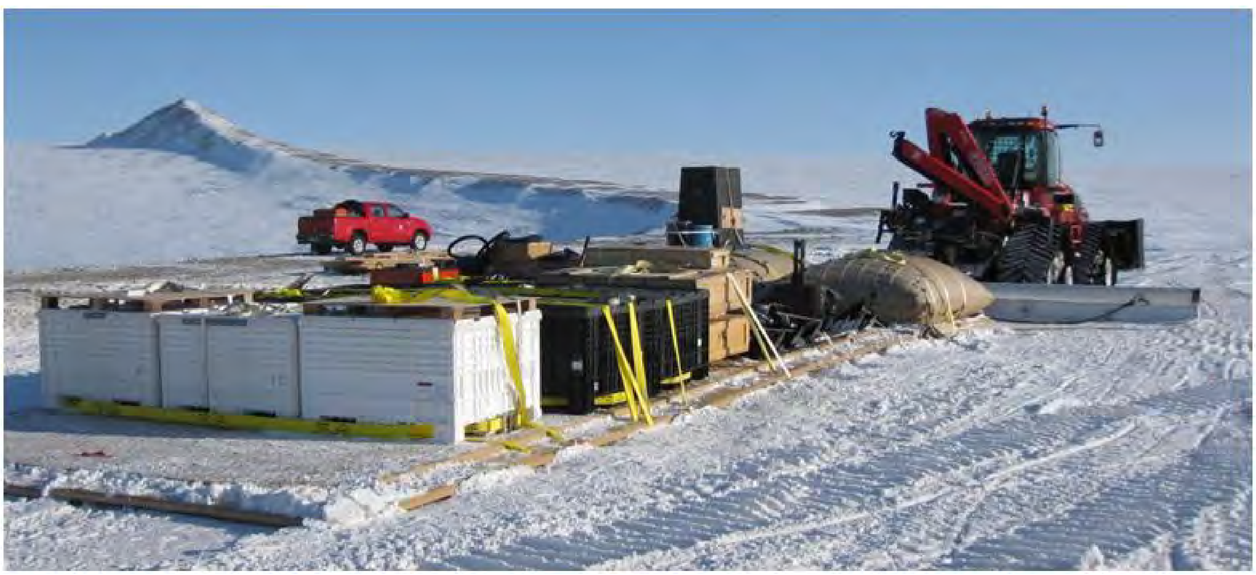

Figure 10. Fuel bladders and rigid cargo loaded onto Dura-Base sled at Thule transition.

GrIT08 encountered long stretches of snow from NEEM to Summit that was softer than the softest snow along the SPoT route (Lever and Weale 2009). Glaciologists Z. Courville (CRREL) and M. Fahnestock (U. New Hampshire) suggested that by deviating the route about 66 miles east of NEEM, the traverse could encounter snow with approximately $^1/_3$ lower annual accumulation and potentially higher strength. GrIT10 adopted this route deviation (Fig. 11). Because Summit lies east of NEEM, the NEEM–Summit route length increased by only 29 miles.

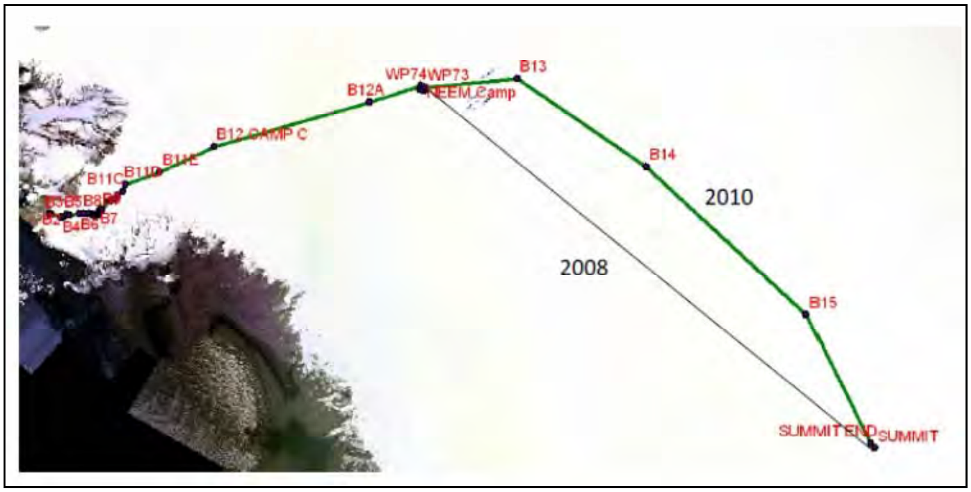

Figure 11. GrIT10 route (green) varied from the 2008 route through the transition (waypoints B0–B11D) to avoid new crevasses and from NEEM to Summit to travel over snow predicted to have lower accumulation and thus higher strength. Total route length increased by 29 miles, from 705 to 734 miles.

3 2010 Season Overview and Comparison with 2008

Figure 12 shows daily advance versus route location for GrIT10 and GrIT08, and Table 1 compares the overall season performances.

Table 1. Overall season performance of GrIT10 compared with GrIT08.

Route segment	Length (mi)	Travel days	Departing Gross Sled Weight (lb)		Arriving Gross Sled Weight (lb)		Payload Delivered	
			Case	Tucker	Case	Tucker	Items	Weight (lb)
2010								
Thule–B11D	70	6	158,600	12,500	155,200	12,500		
B11D–NEEM	226	7	142,400	28,300	142,400	21,200	1500 gal. fuel	10,100
NEEM–Summit	438	10	115,700	31,200	109,000	16,900	11,330 gal. fuel, Case, Tucker, Case & Tucker parts	165,000
Total	*734*	*23*						*175,100*
2008								
Thule–B11D	70	9	154,400	18,300	149,000	18,300		
B11D–NEEM	225	7	149,000	18,300	133,400	18,300	3,000 gal fuel	20,100
NEEM–Summit	410	9	109,000	18,300	63,500	18,300	2,000 gal fuel	13,400
Total	*705*	*25*						*33,500*

The GrIT10 survey team reestablished a safe route from Thule onto the ice cap prior to the departure of the traverse itself (Mercer et al. 2010). While this effort required resources to mobilize, it was more efficient than the combined survey/traverse effort conducted in 2008.

GrIT10 covered the 70 miles from the Thule transition to flat terrain at D11D in 6 travel days plus 1 weather day compared with 9 travel days plus 7 weather/survey days in 2008. The sleds were configured into two trains for planned shuttling: the two dual-bladder sleds on the small spreader (gross weight 86,000 lb), and the Dura-Base sled with the single 3000-gal.

bladder sled on the large spreader (initial gross weight 72,600 lb, reduced by daily fueling).

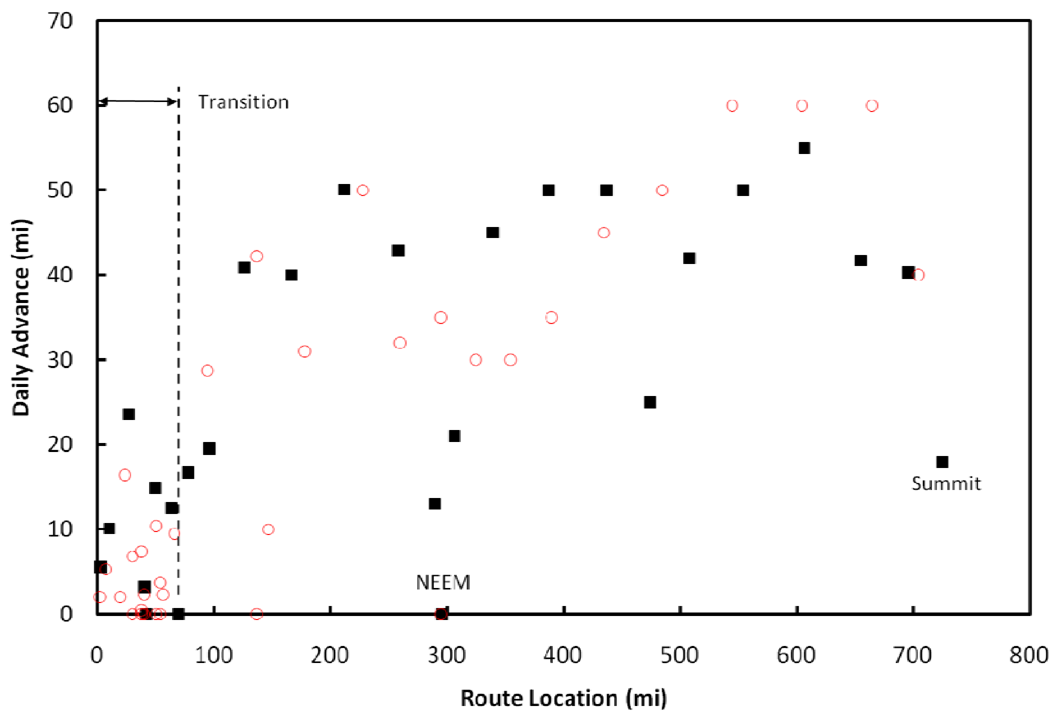

Figure 12. Daily advance versus route location. Progress was much more consistent in 2010 (solid squares) compared with 2008 (open circles) owing to planned shuttling through the transition and overall sled improvements.

Planned shuttling reduced the innumerable immobilizations on steep slopes seen in 2008 to just two. The first occurred on the route's steepest slope, 8% just before B9D, and the second on a 6.7% grade just past B10A. On several occasions, the Tucker assisted the Case by holding back the bladder sleds on down-grades, especially those with side slopes. The small skegs installed under the bladder sleds did not provide sufficient directional control to stabilize the sleds on side slopes, although they did appear to improve directional stability over sastrugi. The Dura-Base sled did not require hold-back assists on downhill or side slopes owing to higher sliding resistance.

The crew shuttled loads for 1 day past B11D, to move away from their weather-in camp, then assembled the dual-bladder and Dura-Base sleds onto the large spreader to tow as a single train to NEEM (gross weight 142,400 lb, Fig. 5). The crew also transferred the 3000-gal. bladder sled to the Tucker sled-train (gross weight 28,300 lb initially, reduced by daily fueling, Fig. 4).

GrIT10 required 7 travel days from B11D to NEEM, including the day shuttling and some time lost to assist the Go North project. No immobilizations occurred. This was better performance than 2008. Although GrIT08 also covered B11D to NEEM in 7 travel days, the Case broke traction on two hills en route to Camp Century and had to shuttle loads on the last day into NEEM. Gross weight shuttled into NEEM in 2008 was less than 2010 (133,400 versus 142,400 lb).

At NEEM, the crew conducted dedicated mobility tests, delivered 1500 gal. of fuel to NEEM, transferred the other 1500 gal. from the Dura-Base sled to refill the 3000-gal. bladder sled, and reconfigured the Dura-Base sled to ride on two 34-ft-long HMW-PE sleds.

Gross weight of the Case sled train departing NEEM in 2010 was 115,700 lb. GrIT10 covered the 438 miles from NEEM to Summit along the new route in 10 days (no weather days) and arrived with the Case towing 109,000 lb. It also devoted approximately 2 hours each day to conduct NSF-funded snow-science experiments rather than increasing daily advance. The Case experienced only one immobilization from NEEM to Summit. By comparison, GrIT08 covered 410 miles from NEEM to Summit in 9 days, but was forced by poor mobility to shuttle 109,000 lb for the first 2 days out of NEEM until caching the empty steel fuel tank. After subsequently caching a fuel bladder for the return trip, it arrived at Summit towing only 63,500 lb. This light load permitted a higher daily advance.

4 Sled Resistance

It is helpful to identify several components of sled-train resistance to understand sled performance and to plan season loads. A tractor must first overcome sled startup resistance. For SPoT bladder sleds, at temperatures below about −20°C, resistance over the first few minutes of motion can be substantially higher than steady state resistance until the sleds warm up. Startup at low temperatures can thus be the limiting load-planning factor. To keep the sleds moving over many hours, a tractor must also overcome average resistance plus frequent peaks caused by variations in snow conditions. We normally use $T = R + 3\sigma_R$, where R is the average resistance and σ_R is its standard deviation, to characterize steady state sled-train resistance for load-planning. The separate contributions are also of interest. Average resistance, R, includes resistance from sliding friction and snow compaction (i.e., deformation of the snow that produces ruts). The ratio of $3\sigma_R/R$ indicates the relative importance of snow variations (sastrugi, soft snow, etc.) to average conditions. It can be particularly high for steel sleds owing to feedback between snow compaction and sled motion (or “porpoising”).

Figure 13 shows steady state resistance T, measured at the Case hitch, per unit weight of the sled train versus location along the route. Weight, W, is gross sled weight and thus includes sled tare weight and weight of the spreader bar. All data were from the relatively flat terrain beyond B11A.

Separate shuttling of the bladder and Dura-Base sleds from B11A to past B11D allows quick comparison of the towing performance of the two sled types. Note that the shuttled Dura-Base sled-train also included the single 3000-gal. refueling bladder sled. This train had significantly higher resistance per unit weight than the two dual-bladder sleds (average $T/W = 0.17$ vs. 0.10, respectively). Because the single 3000-gal. sled probably improved the combined-train performance, T/W for the Dura-Base sled was probably higher.

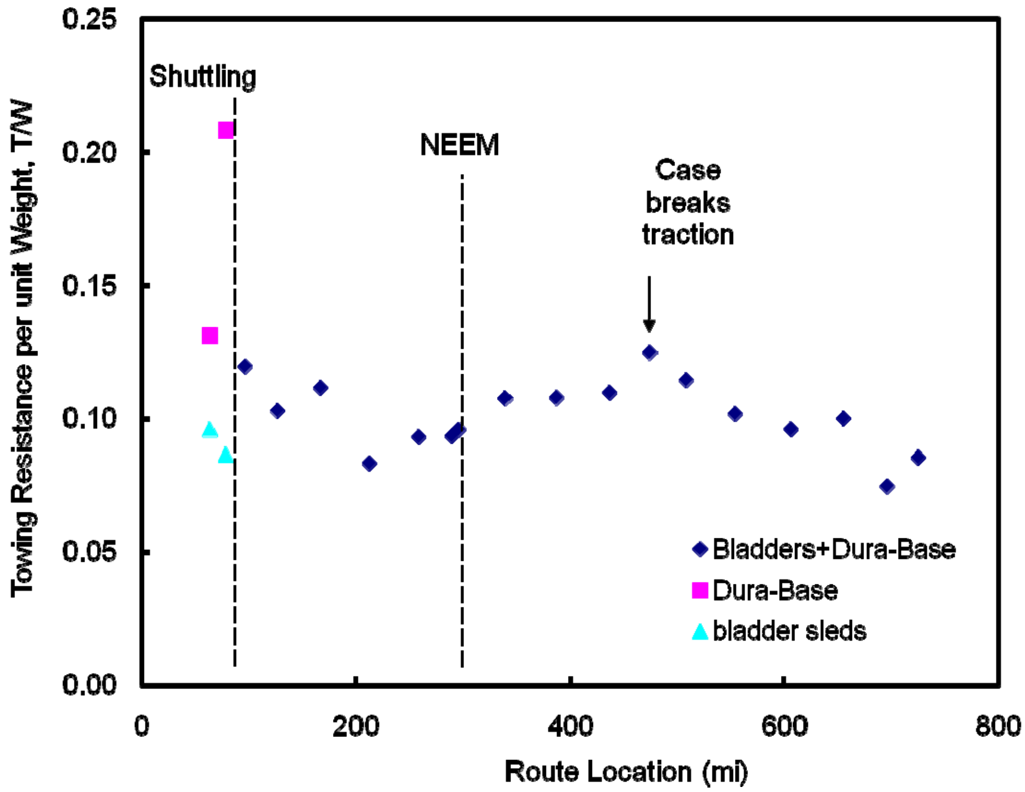

Figure 13. Towing resistance per unit gross weight (*T/W*) versus route location over essentially flat terrain. Except for 2 days of shuttling, the Case towed all heavy sleds as a single train.

This result was later confirmed through dedicated tests at NEEM: T/W = 0.18 for the Dura-Base sled alone on the short spreader; T/W = 0.096 for the dual-bladder sleds on the outside of the large spreader. Note that the Dura-Base sled also had lower payload fraction (payload/gross weight) than the bladder sleds (0.82 vs. 0.95, respectively). That is, per weight of payload carried, W_p, the Dura-Base sled was much less efficient than the bladder sleds (T/W_p = 0.22 vs. 0.10, respectively).

After mile 78, the Case towed all heavy sleds as a single sled train at average $T/W = 0.10 \pm 0.01$ and broke traction only once (mile 475 or ~ 180 miles outbound from NEEM). This compares very well against GrIT08, where the HMW-PE bladder and cargo sleds averaged $T/W = 0.13 \pm 0.04$ over the whole route and $T/W = 0.16 \pm 0.01$ after NEEM. Because the Dura-Base sled was lightly loaded after NEEM, the GrIT10 single-train towing resistance was dominated by the good performance of the dual-bladder HMW-PE sleds.

Load shackles on the spreader bar directly measured the towing resistance of the two dual-bladder sleds: Sled1 (heating blankets) and Sled2 (black covers). Thermocouples measured the sled–snow interface temperature along each sled. Figure 14 shows the relationship between the two. Here, we plot average towing resistance, R, because it is equivalent to sliding friction provided snow-compaction resistance (i.e., rut depth) is small. Low scatter in the results suggests that, regardless of method, increasing sled temperature lowers steady-state towing resistance until interface temperature reaches approximately −5°C. Increases in sled temperature above approximately −2°C can increase resistance. This trend is consistent with the theory of snow friction for polyethylene-base skis (Colbeck 1992; Bäurle et al. 2007) and with CRREL's preliminary model of bladder-sled resistance based on that theory (Kaempfer and Lever 2009). Interface temperature largely governs bladder-sled towing resistance.

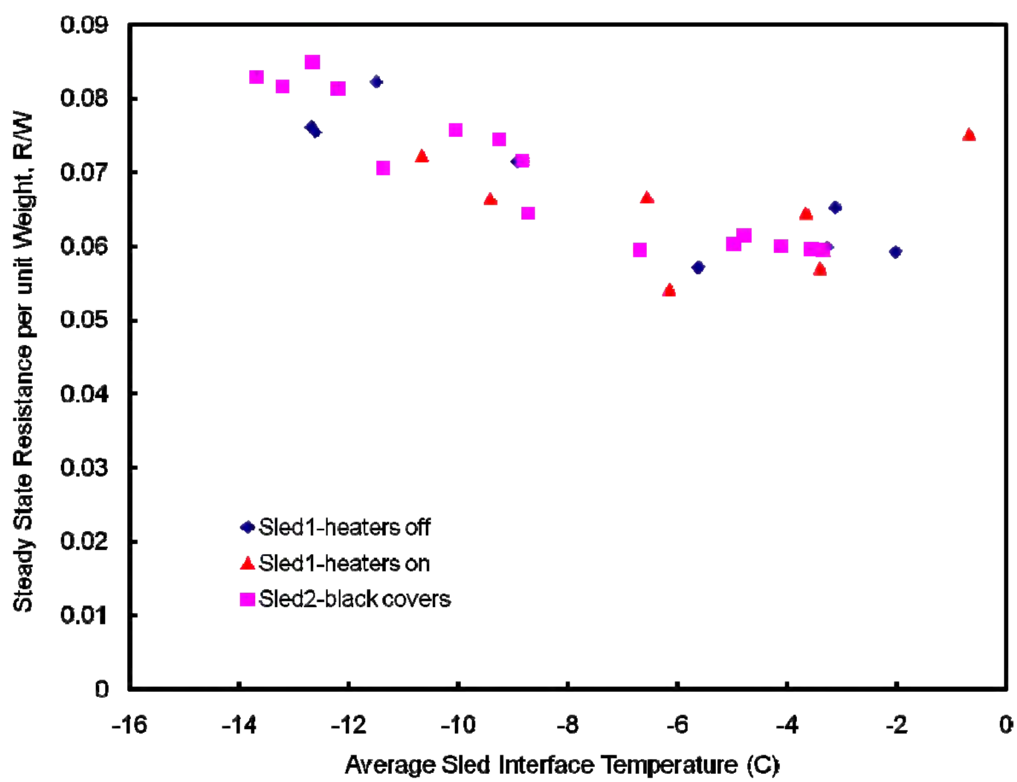

Figure 14. Steady state resistance of dual-bladder sleds versus sled-snow interface temperature. Resistance decreases with increasing temperature in all configurations (heaters on/off, black covers) until ~ −5°C. Resistance can increase if interface temperatures exceed ~ −2°C.

The data in Figure 14 are for two 3000-gal. bladders inline on the same sled. However, interface temperatures were 1–2°C higher under the second bladder compared with the first. Consequently, the second bladder contributed less resistance than the first as the passing sled continued to warm the snow and increase meltwater thickness. This effect probably accounts for much of the improvement in performance of the GrIT10 dual-bladder sleds compared with the GrIT08 single-bladder sleds. We plan to investigate this effect, as well as the role of temperature distribution along the sleds, as we examine the data in more detail and finalize the sled–friction model (Kaempfer and Lever 2009).

We may infer the towing resistance of the Dura-Base sled within the full sled-train by subtracting the measured resistances of Sled1 and Sled2 from the total train resistance and allowing for the resistance of the spreader bar (~ 1200 lb based on NEEM mobility tests). Figure 15 compares bladder-sled and Dura-Base resistances as functions of air temperature. While air temperature does not collapse bladder-sled resistance as well as sled-interface temperature, it is a convenient surrogate.

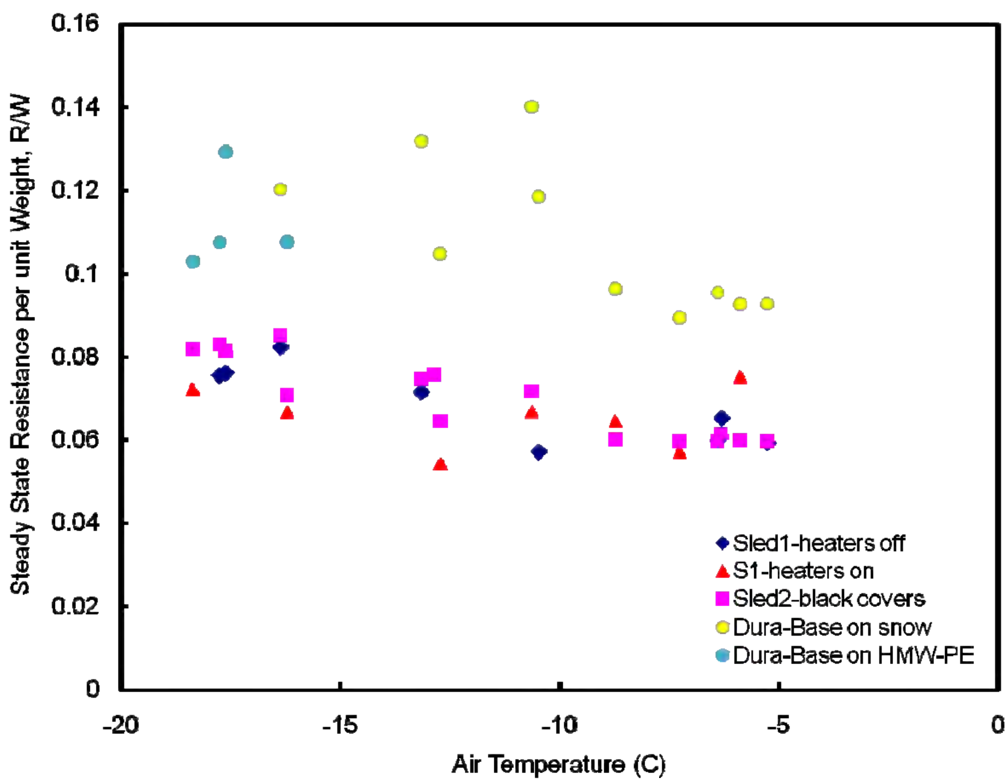

Figure 15. Comparison of fuel-bladder sleds with Dura-Base cargo sled, average resistance per unit weight versus air temperature.

The Dura-Base sled performed slightly better after being placed on HMW-PE sleds at NEEM. Nevertheless, the bladder sleds were significantly more efficient at all air temperatures, and the performance advantage increases to about 2:1 if calculated per weight of payload carried. These results are consistent with those obtained from shuttling the loads separately and with the dedicated tests at NEEM.

Figure 16 shows an important comparison of the average towing resistance per unit weight, *R*/*W*, versus air temperature of unheated dual-bladder sleds used during SPoT08-09, SPoT09-10, and GrIT10. For all air temperatures, SPoT's sleds produced significantly less resistance than GrIT's. Fortunately for GrIT, seasonal air temperatures are higher so that the practical range of towing resistance is similar to that for SPoT.

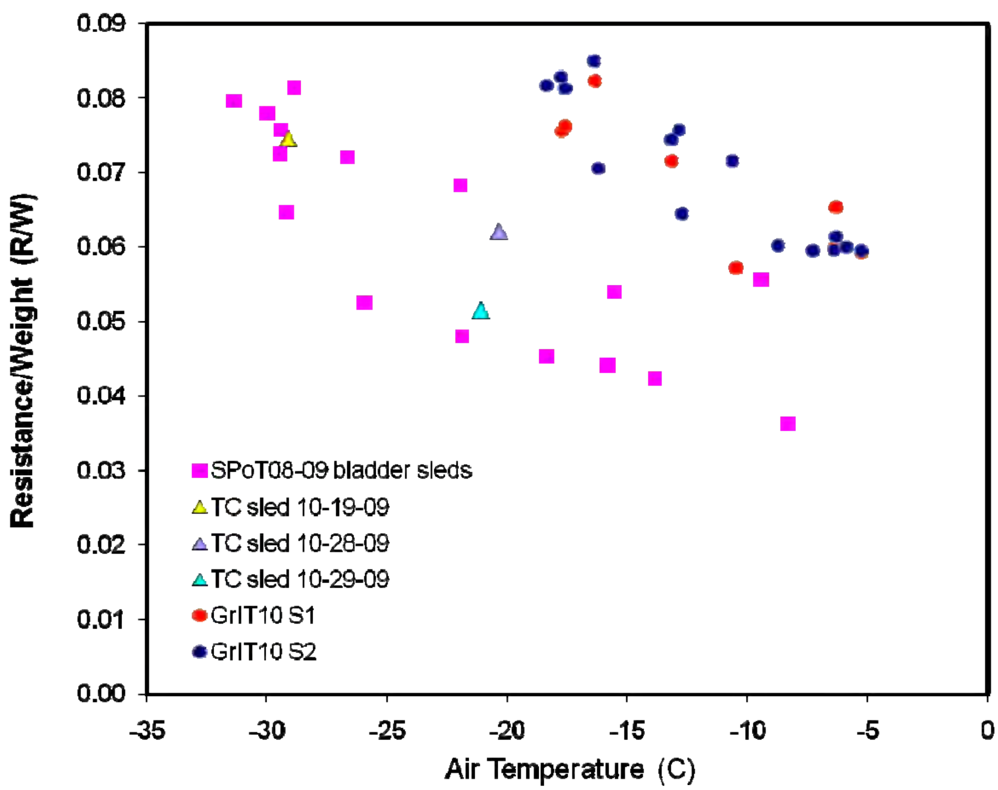

Figure 16. Steady state resistance per unit weight (*R*/*W*) versus air temperature for unheated dual-bladder sleds during SPoT08–09 (squares), mobility tests preceding SPoT09-10 (triangles), and GrIT10 (circles). For a given air temperature, the GrIT10 bladder sleds displayed higher resistance, suggesting that other factors are involved.

Why do SPoT bladder sleds tow easier than identical GrIT sleds? It's possible that the generally clearer skies in Antarctica compared with Greenland warm the bladders so that sled interface temperatures are higher for the same air temperatures. We are investigating this possibility. The softer snow in Greenland could also account for higher towing resistance, although not via snow-compaction resistance because rut depths produced by bladder sleds are negligible in both locations. However, softer snow should increase contact area between the sled and surface snow grains; frictional heating would thus be spread over larger areas, producing thinner meltwater layers and consequently higher friction. This is a snow-surface phenomenon that is not well captured by Rammsonde snow-penetrometer measurements. We have taken surface-snow samples after sled passage in both Antarctica and Greenland and will examine these microscopically to determine whether contact areas are significantly different.

GrIT10's two bladder sleds were configured to assess the benefits, if any, of active heating versus passive solar gain to increase sled–snow interface temperature and thereby reduce sled resistance. These benefits could come in the form of reduced startup or steady state resistance. Pre-season modeling suggested that, depending on wind speed and solar irradiance:

- Black bladders could be nearly as effective as 300 W/m^2 insulated heating blankets, and more effective than insulation alone, at reducing steady state friction.
- Black bladders could reduce startup resistance by allowing the sled to be warmer than the air temperature at startup.
- The main benefit of the heating blankets would be to reduce startup resistance, provided they are turned on before startup. The heaters produce less benefit under steady state conditions.
- Insulation alone (i.e., heaters off) provides little benefit and could increase startup resistance compared with an uninsulated sled.

GrIT had insufficient lead time to obtain black fuel bladders, so we used sheets of black rubber to increase solar gain for the two bladders on Sled2 (Fig. 4). Although we initially fit them tightly, the covers were probably less efficient than black bladders owing to incomplete coverage and increasing air gaps and snow intrusion caused by numerous snow storms. We expect that black bladders will out-perform the black covers used during GrIT10.

At our request, the crew often operated the heating blankets for half days to obtain data for Sled1 in both conditions over similar snow and air temperatures. The blanket insulation was, of course, present in either case.

The heaters were generally turned on 15–30 minutes before moving the sleds.

Figure 17 shows the warming benefit of the three test configurations, Sled1—heaters off (insulation only), Sled1—heaters on, and Sled2—black covers, in terms of steady state sled interface temperature rise versus air temperature. Heaters-on produced the largest warming benefit, followed by heaters-off (insulation), with black covers causing the least increase in sled interface temperature. All three configurations produced larger warming at lower air temperatures. This is a helpful effect to decrease snow friction and is probably related to higher frictional heating at lower temperatures.

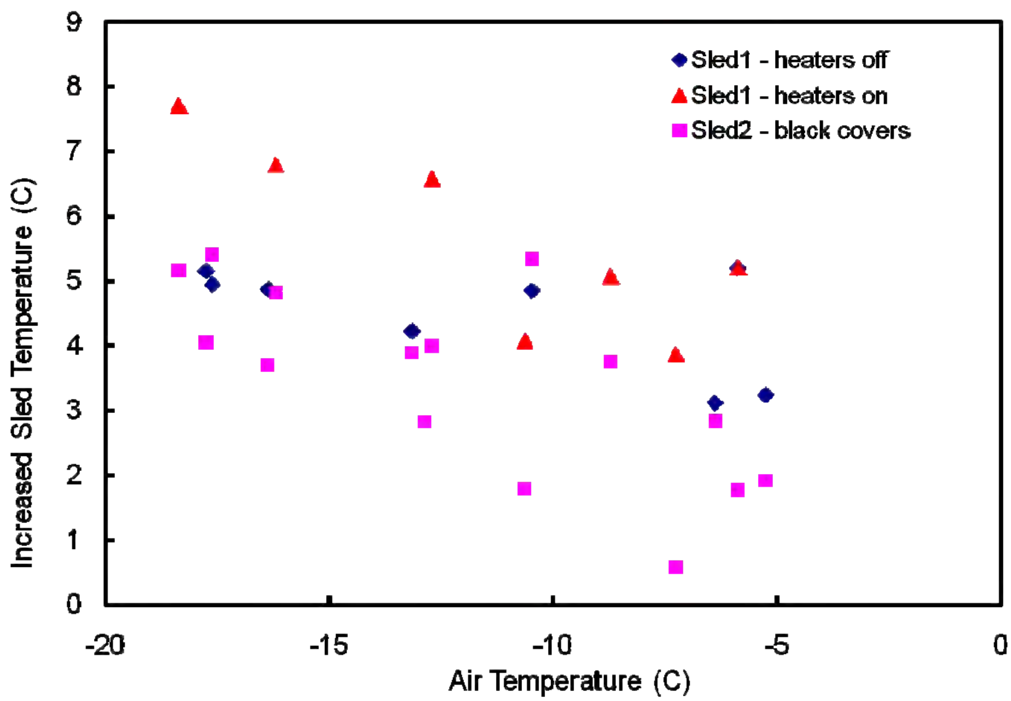

Figure 17. Increased steady state sled interface temperature versus air temperature for the three sled configurations tested. Heaters-on produced the largest warming benefit and black covers the least. The benefit for all configurations increased with colder air, a helpful effect probably related to frictional heating.

Interestingly, the increased warming benefit of the heating blankets does not produce dramatically better towing resistance compared with the black covers. Figure 18 shows Sled1 startup and steady state resistance relative to Sled2, for heaters on and off, plotted versus air temperature. For startup resistance, we use R_{peak}, the highest 10-s average value near startup (excluding the first tug where momentum spikes often occur). For steady state here we use *R*, although the results would be essentially the same using *T*.

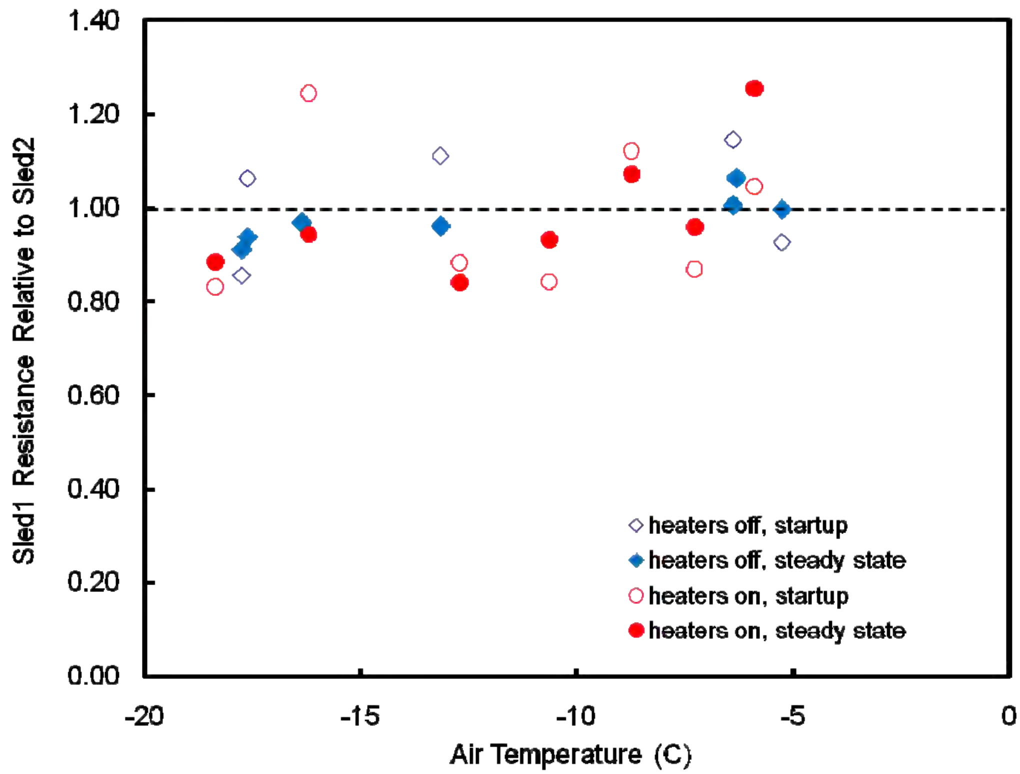

Figure 18. Resistance versus air temperature of Sled1 (heaters off/on) at startup and steady state relative to corresponding resistance of Sled2 (black covers).

Any resistance benefits of the heating blankets relative to black covers occurred for air temperatures below about −10°C. In this regime, turning the heaters on produced a startup benefit of about 15% (ignoring one outlier at −16°C) and a steady state benefit of around 10%. With the heaters off, the insulation produced no startup benefit and only approximately 5% steady state benefit. For air temperatures higher than -10 C, the heating blankets, whether on or off, generally performed slightly worse than the black covers.

At present, the minor benefits of heating blankets in colder weather do not appear to justify their cost and operational complexity compared with black covers. Use of more thermally efficient black bladders would likely eliminate this small benefit in any event.

Figure 19 shows the components of resistance (R_{peak}/W, T/W, and R/W) versus air temperature for GrIT10 full sled trains (Sled1, Sled2, and Dura-

Base sled on large spreader). All three resistance components show a slight decrease with increasing temperature; not unexpectedly, R_{peak} shows the most scatter. Interestingly, startup resistance was not substantially higher than subsequent steady state resistance: $R_{peak}/W = (1.06 \pm 0.08) \times T/W$ across all temperatures. That is, for load planning, essentially either measure may be used. This is unlike the case for SPoT, where startup resistance at low temperatures dictates maximum sled-train loads, and reflects the fact that air temperatures below −20°C were not common during GrIT10.

By comparing T/W and R/W, Figure 19 also demonstrates that snow-strength variations do not strongly influence sled-train resistance. Across all temperatures, $T/W = (1.14 \pm 0.03) \times R/W$, indicating that $3\sigma_R/W = 0.14$, a relatively small contribution and consistent with SPoT bladder sleds. By comparison, steel sleds typically have $3\sigma_R/W > 0.5$ owing to a greater role of snow-compaction resistance. That is, the benefits of flexible sleds include lower average resistance and smaller variations in resistance compared with steel sleds.

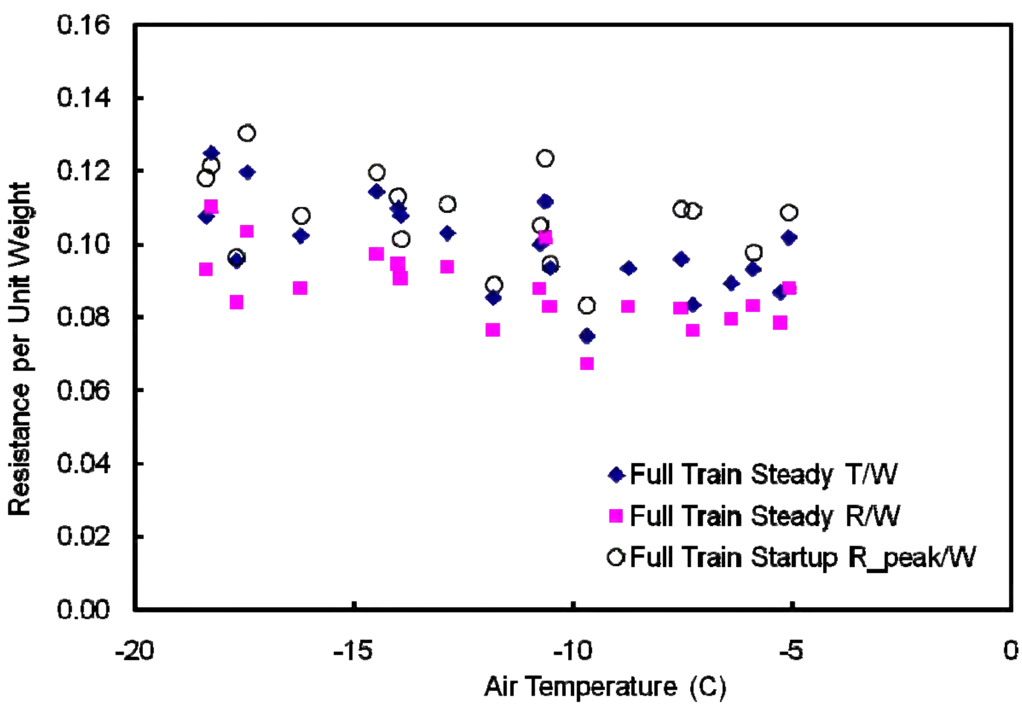

Figure 19. Comparison of resistance components measured at Case hitch for full sled trains (two bladder sleds and Dura-Base cargo sled). Steady state $T/W = R/W + 3\sigma_R/W$ to account for variations in snow condition. Startup R_{peak}/W is similar in magnitude to steady T/W.

5 Tractor Performance and Route Deviation

As noted, the Case broke traction twice on steep hills along the transition and only once on the flat snow beyond B11A (at ~ 180 miles past NEEM). Peak drawbar-pull (10-s average) through the transition for the two immobilizations and one successful pull up a 2.4% grade was $DBP = 21{,}600 \pm 1500$ lb or $DBP/W_{\text{Case}} = 0.32 \pm 0.02$ per unit weight of the Case (W_{Case}). These values are nearly identical to those from GrIT08 through the traction-limited region to NEEM, namely $DBP = 21{,}000 \pm 2000$ lb or $DBP/W_{\text{Case}} = 0.33 \pm 0.03$, a somewhat disappointing result given the use of 20% wider tracks in 2010. However, Case weight increased by 9%, from 64,000 lb in 2008 to 69,500 lb in 2010, so average track pressure decreased by only 11%.

For the single post-transition immobilization in 2010, the Case developed only 14,700 lb of drawbar just before breaking traction ($DBP/W_{\text{Case}} = 0.22$). However, Case rut depth of 16 in. at this location was the highest for the 2010 trip, and the tractor was dragging its hitch and probably its rear belly pan. That is, self-propulsion resistance was very high, and this reduced net traction available to tow the sleds.

In 2010, Case rut depths averaged 7.2 ± 1.2 in. to NEEM and 8.9 ± 4.0 in. from NEEM to Summit. These were shallower than in 2008 for both route segments (10 ± 2 and 12 ± 2 in., respectively). Figure 20 compares snow strength measurements (Rammsonde energy to penetrate top 60 cm) versus route location for the two seasons. The data were sparse in 2008 but show weaker snow along the route except for the last roughly 200 miles into Summit. These data could account for the shallower ruts made by the Case in 2010 and indicate that the tractor used less of its available traction and power for self-propulsion.

It is unclear whether the 2010 easterly route deviation or seasonal weather differences account for the higher snow strengths encountered for 200 miles past NEEM. Glaciologist Z. Courville accompanied GrIT along this section and conducted snow-pit observations and measurements. Her initial thoughts are that seasonal variations (upper-level snow deposition and metamorphism) affect the traverse more strongly than geography and climate. Nevertheless, the 2010 deviation amounted to less than 1 day's average advance, and higher snow strengths were indeed encountered. It might be possible to assess the merits of the deviation during GrIT11 by, say, heading outbound along the 2010 route and returning along the 2008 route, while making daily snow-strength and snow-pit measurements. This could be a good match of the interests of GrIT and Greenland snow science.

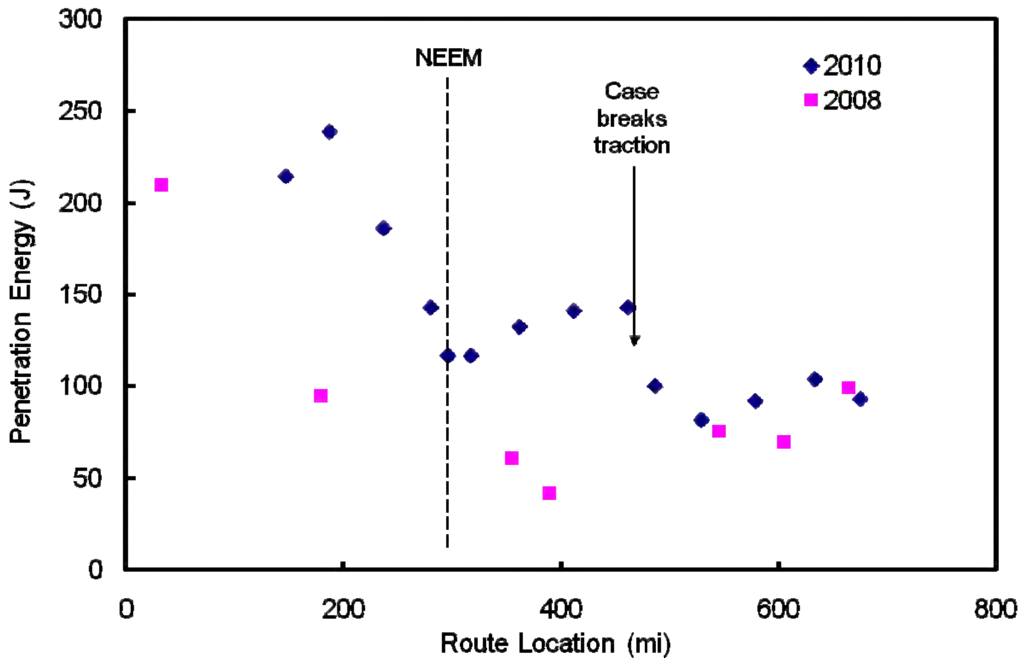

Figure 20. Snow strength (Rammsonde energy to penetrate top 60 cm) versus route location for 2008 and 2010 routes. The Case broke traction at numerous locations departing NEEM in 2008, necessitating shuttling. In 2010, the single immobilization occurred as snow strength abruptly dropped and towing resistance spiked (see Fig. 13) owing to low air temperature.

6 Implications for Future GrIT Re-Supply Operations

Lever and Weale (2009) made several mobility projections to analyze GrIT economic feasibility. These projections are largely confirmed by GrIT10 mobility data and overall fleet performance:

- A well-balanced Case weighing about 70,000 lb and fitted with 36-in.-wide tracks should reliably achieve *DBP* = 21,000 lb.
  - The Case achieved *DBP* = 21,600 ± 1500 lb and broke traction only once beyond the transition.
- The Tucker Sno-Cat should be able to tow crew accommodations and all fleet supplies except fuel.
  - GrIT10 did not include the envisioned crew quarters; fleet food and spare parts were mostly carried on the Dura-Base sled towed by the Case. Nevertheless, the Tucker reliably towed the wannigan, orange sled, and 3000-gal. (~ 20,000 lb) of fuel, a comparable total payload.
- GrIT can implement half-load shuttling along the 60-mile transition to reduce immobilizations from steep slopes.
  - GrIT10 shuttled the two dual-bladder sleds and the Dura-Base cargo sled through the transition with only two immobilizations, both on very steep slopes. Transit time through the transition decreased from 9 travel days in 2008 to 6 in 2010, and the reduced number of immobilizations decreased strain on the crew.
- Tow fuel only in bladders on flexible sleds and omit the inefficient steel tank sled.
  - The average for all GrIT10 heavy sleds (two dual-bladder sleds and Dura-Base) towed as a single train was T/W = 0.10 ± 0.01. This was substantially better than the average for the tank sled towed during GrIT08 (T/W = 0.41 ± 0.08).

Lever and Weale (2009) then examined the long-term economic feasibility of GrIT based on a three-tractor fleet (two Case towing tractors and a Tucker support vehicle) resupplying NEEM and Summit via a single round-trip per season. They varied the number of bladders (or equivalently efficient cargo sleds) towed per Case to identify the mobility performance needed for GrIT to break even economically. Benefits were derived from LC130 savings (flying hours and positioning costs) for flights offset by traverse, while costs included best-estimates (with 20% contingency) of annualized capital and operating costs for the traverse.

The analysis indicated that at then-current LC130 SAAM rate ($6800/hr) each Case would need to tow 10 bladders outbound from Thule for GrIT to break even. If SAAM rates increased 20% to $8200/hr, GrIT would break even at a performance of eight bladders per Case. GrIT can also generate benefits not included in the analysis, such as transporting heavy and outsized cargo, significantly reducing air emissions, conducting science or resupplying camps along the route, and hedging against unrestrained LC130 costs. Nevertheless, for economic breakeven, the authors concluded that:

> The critical route segment is from just past the transition to NEEM, a distance of about 230 miles where current performance is about 7 bladders per Case and a performance of 8–10 is needed. GrIT could achieve the needed performance with a modest sled-development effort.

GrIT10 achieved the needed performance. We may demonstrate this with an analysis based on average sled resistance and confirm it with an independent analysis that allows for temperature-dependent sled resistance.

The gross weight of ten 3000-gal. fuel bladders on HMW-PE sleds (plus one large and one small spreader) is 216,000 lb. GrIT10 shuttling from B11A (Sled1 and Sled2 on small spreader, sleds riding in Case ruts) and mobility tests at NEEM (Sled1 and Sled2 on large spreader, sleds outside of Case ruts) produced resistance coefficients T/W = 0.10 and 0.096, respectively. After mile 78, the Case towed all heavy sleds (Sled1, Sled2, and Dura-Base sled on large spreader) as a single sled train at average T/W = 0.10 ± 0.01, an upper bound for bladder–sled resistance because the Dura-Base sled consistently developed higher resistance. Thus, based on steady state resistance data, the towing resistance of a 10-bladder train would be

T = 216,000 lb × 0.10 = 21,600 lb. This is right at the measured drawbar capacity of the Case tractor in 2010 trim developed, DBP = 21,600 ± 1500 lb. Even allowing for some reserve capacity, the Case should easily tow the eight-bladder train needed to break even for 20% increased SAAM rates.

An analysis that allows for temperature effects on bladder–sled resistance confirms this result. GrIT10 yielded a wealth of data on the performance of dual-bladder sleds that excludes the resistance of the Dura-Base sled. Figure 15 shows that at the lowest air temperatures encountered during GrIT10 (−18°C), the highest sliding resistance of dual-bladder sleds measured at the spreader bar was $R/W = 0.085$ (black covers) and decreased with increasing air temperature. We may use the upper value, apply the measured ratio of $T/R = 1.14$ and boost the result slightly for startup resistance ($R_{peak}/T = 1.06$) to determine that $R_{peak}/W = 0.103$ for load planning. This is the estimated resistance for the sleds, so we must add in spreader-bar resistance (~ 1200 lb). Four dual-bladder sleds (W = 169,600 lb) plus a large spreader would thus require a drawbar capacity of R_{peak} = 169,600 lb × 0.103 + 1200 = 18,600 lb, well within the measured Case capacity of 21,600 lb. Indeed, the reserve capacity of 3000 lb is sufficient to tow about 1.4 additional bladders on HMW-PE, for a total sled train of 9.4 bladders towed at the lowest air temperature encountered during GrIT10.

These results indicate that GrIT's current performance is sufficient to achieve a target of eight 3000-gal. fuel bladders per Case tractor outbound from Thule to satisfy economic breakeven at 20% increased SAAM rate ($8200/hr). The higher target of 10 bladders per Case for breakeven at $6800/hr SAAM rate is also within reach. As noted, black bladders will out-perform black covers in terms of solar gain, resulting in warmer sleds and lower resistance. The benefit will be most noticeable at the low air temperatures that govern load-planning resistance.

Interestingly, GrIT's 8–10 bladder tractor capacity is identical to the current load limit for SPoT. Warmer air in Greenland compensates for weaker snow conditions to yield the same seasonal load limits.

Several other points are worth noting. Lever and Weale (2009) treat fuel and cargo identically to estimate economic breakeven. Because GrIT must transport significant cargo payloads, it needs to tow cargo nearly as efficiently as fuel. This need underlies the recent GrIT/SPoT/CRREL joint effort to develop efficient, lightweight cargo sleds for Polar traverses (Lever and Gooch 2010; Lever 2010a, 2010b). Indeed, GrIT will trial two air-pillow cargo sleds during the 2011 season as part of this development effort.

Also, it is reasonable in terms of season efficiency to set sled-train loads near the upper limit of tractor capacity and tolerate a few immobilizations along the route. Nevertheless, allowing for reserve capacity by slightly reducing loads is an acceptable compromise. The towing tractors will experience very few if any immobilizations, and they can convert unused capacity (specifically reserve power) into higher travel speeds, which shortens travel time and saves fuel. This conservative approach also reduces crew stress and improves schedule reliability, important considerations for long-term sustainability of GrIT.

GrIT11 will operate with two newly procured Case 485 Quadtracs. GrIT intentionally purchased lighter (57,000 lb) Quadtracs with the same 485-hp engines and 36-in.-wide tracks as the GrIT10 Case delivered to Summit. Average ground pressure will drop from 6.6 to 5.4 psi, which should significantly decrease tractor rut depths and self-propulsion resistance. This benefit, as with sled improvements, can be self-reinforcing: the tractors should develop more drawbar power, which allows higher towing speeds, which increases frictional heating of the sleds, which lowers sled resistance.

Lower ground pressure of the Quadtracs could also increase maximum drawbar pull per unit weight, DBP/W, compared with GrIT10 trim. If this latter benefit is not realized, Case drawbar capacity would scale with its weight and thus drop to about 18,000 lb. This lower value might still be sufficient to tow eight 3000-gal. fuel bladders but with little reserve capacity. For this reason, and because the new air-pillow cargo sleds are untested, we have recommended that GrIT11 set its load limit equivalent to seven bladders per Case. The resulting configuration will be six 3000-gal. bladders and one cargo sled (~ 15,000-lb payload) on four sheets of HMW-PE behind a large spreader. After assessing the 2011 mobility data, we can determine whether the Cases should be ballasted to increase their drawbar capacity or left as-is to capitalize on their lower ground pressure.

GrIT11 will also use a new Case Magnum 335 tractor, outfitted with Soucy tracks, as its fleet-support vehicle. It is a 335-hp quad-track tractor weighing about 36,300 lb with average ground pressure of about 5.6 psi. We may estimate its towing capacity as *DBP* approximately 12,000 lb based on the measured performance of the GrIT08-10 Quadtrac (*DBP*/*W* ~ 0.33). The Magnum will have lower ground pressure, so its *DBP*/*W* could be higher. Indeed, tests conducted on a similar John Deere 8530 tractor equipped with similar Soucy tracks yielded *DBP*/*W* = 0.38–0.40 over natural, groomed, and pack-trail snow conditions in Quebec (Lever and Weale 2009). Nevertheless, *DBP* of about 12,000 lb is substantially higher than the Tucker SnoCat it replaces (*DBP* = 8000 ± 400 lb; Lever and Weale 2009) and results in a load limit equivalent to over five bladders, essentially the round-trip fuel needed for the GrIT11 fleet.

7 Summary and Conclusions

In 2008, the inaugural 705-mile Greenland Inland Traverse from Thule Air Base to Summit Station encountered mobility problems that reduced its season performance: a) numerous steep slopes along the 60-mile transition onto the main ice sheet caused frequent immobilizations and shuttling of sled trains, b) soft snow along much of the route increased tractor sinkage and self-propulsion effort, and c) sled towing resistance, especially for the steel tank sled, was significantly higher than expected. Consequently, GrIT implemented several changes to improve performance for its 2010 traverse:

- Planned sled-train shuttling through the transition.
- Wider tracks on the Case to reduce ground pressure.
- An eastward route deviation from NEEM to Summit to travel over lower-accumulation snow.
- Elimination of the steel fuel-tank sled.
- Towing bladders two inline on longer HMW-PE sleds.
- Trial of active and passive heating to warm the bladder sleds.
- Use of a new spreader bar.
- Trial of a semi-rigid plastic cargo deck (Dura-Base).

GrIT10 reestablished a safe route onto the Greenland ice cap from Thule to resupply NEEM and Summit Station. Planned shuttling of half-loads through the transition was very effective: it reduced numerous immobilizations on steep slopes seen in 2008 to just two in 2010 and cut travel time to flat terrain at B11D from 9 to 6 days.

Overall season performance was also much better in 2010. The Case Quadtrac towed a higher gross weight into NEEM without needing to shuttle and with no immobilizations. It hauled all heavy sleds as a single train outbound from NEEM and experienced only one immobilization en route to Summit. Although transit time NEEM–Summit (10 days) was 1 day longer than in 2008, the Case arrived towing 109,000 versus 63,500 lb in 2008, and the crew devoted about 2 hours each day to conduct NSF-funded snow-science experiments. GrIT's delivered payload increased from 33,500 lb in 2008 to 175,100 lb in 2010, in large part through the delivery to Summit of the Case and Tucker tractors.

Case drawbar capacity averaged DBP = 21,600 ± 1500 lb or DBP/W_{Case} = 0.32 ± 0.02, essentially unchanged from 2008. Higher tractor weight probably offset expected benefits from wider tracks. Measured snow strengths were higher in 2010, which could account for some fleet performance improvement. It is not clear whether the eastward route deviation or seasonal weather differences account for higher strengths for 200 miles outbound from NEEM, but fleet performance was certainly better and the extra route length (29 miles) amounted to less than 1 travel day.

Towing resistance of the heavy sleds substantially improved in 2010. After mile 78, the Case towed all heavy sleds as a single sled train at average T/W = 0.10 ± 0.01 and broke traction only once. This compares very well against GrIT08, where shuttling of half loads was frequently necessary. In 2008, trains consisting of HMW-PE bladder and cargo sleds averaged T/W = 0.13 ± 0.04 over the whole route and T/W = 0.16 ± 0.01 after NEEM, tank-cargo sled trains averaged T/W = 0.26 ± 0.04, and the steel tank developed T/W = 0.41 ± 0.08 estimated resistance. Daily fueling was easily accomplished from fuel bladders in 2010, so fleet performance certainly benefited by omitting the steel tank sled.

Significant performance improvement also resulted from changes to the fuel-bladder sleds. We guided these changes with a better understanding of the role of sled-interface temperature on snow–sled sliding friction, the dominant resistance source for bladder sleds. The GrIT10 bladder sleds included instruments to quantify this resistance–temperature dependence.

The two GrIT10 bladder sleds each consisted of two 3000-gal. fuel bladders inline on single sheets of HMW-PE, compared with four similar bladders on four separate sheets in 2008. Longer sleds allow for longer-duration frictional heating over the snow, which in turn produces thicker meltwater layers to lower sliding resistance. We also configured the bladder sleds to assess the benefits, if any, of active heating versus passive solar gain to increase sled–snow interface temperature and thereby reduce sled resistance. Sled1 used insulated heating blankets between the bladders and the sled to test two configurations: heaters on, heaters off (insulation only). Sled2 had thin, black-rubber covers over the bladders to increase solar gain.

Some performance improvement resulted from longer sled length. Average interface temperatures were 1–2°C higher under the second bladder on either sled, suggesting lower net resistance for dual-bladder sleds compared with GrIT08 single-bladder sleds. The GrIT10 sleds probably also ran warmer than those in 2008 owing to the presence of the heating blankets and the black covers. Average bladder-sled towing resistance correlated well with average sled-interface temperature, regardless of method to make the sled warmer (active heating, insulation, or solar gain). Sled resistance decreased with increasing interface temperature until about −5°C; higher interface temperatures produced no additional benefit.

Interestingly, for a given air temperature, GrIT10 bladder sleds developed more resistance than similar South Pole Traverse (SPoT) sleds. We are investigating whether cloudier conditions or softer snow account for this difference. Luckily, Greenland air temperatures are generally higher than Antarctic ones during their respective traverse seasons, so seasonal load limits based on maximum sled-train resistance end up being similar in both locations.

Compared with black covers, the resistance benefits from the heating blankets were small and limited to air temperatures below −10°C, namely 10–15% benefit with the heaters on and 0–5% benefit with the heaters off (insulation only). For air temperatures higher than −10°C, the heating blankets, whether on or off, generally performed slightly worse than the black covers. At present, the minor benefits of heating blankets at lower temperatures do not appear to justify their cost and operational complexity compared with black covers. Use of more thermally efficient black bladders would likely eliminate this small benefit in any event.

The new spreader bar performed well during GrIT10. It is easier to use, lighter weight, and less expensive than the triangular spreaders used in 2008. The design now includes a smoother nose shape and is sufficiently easy to build that the crew built a short version in Thule, using local materials, to help with half-load shuttling through the transition.

The Dura-Base cargo sled was an operational success. It was easy to assemble and load, and it stayed intact throughout the traverse to Summit. Cargo rode nicely on the sled and required little re-strapping, a big improvement from the slip-sliding behavior of cargo transported directly on HMW-PE sleds during GrIT08. Unfortunately, the resistance coefficient of the Dura-Base sled was substantially higher than that of the bladder sleds across all conditions, and resistance per unit weight of payload was essentially twice higher. This underscores the need to continue a GrIT/SPoT/CRREL effort to develop efficient, lightweight cargo sleds. GrIT11 will trial two air-pillow cargo sleds as part of this effort.

Lever and Weale (2009) examined the long-term economic feasibility of GrIT to resupply NEEM and Summit via overland traverse compared with the status-quo of LC130 aircraft resupply. Analyzing a single-swing, two-towing-tractor scenario, the authors concluded that the critical route segment is from just past the transition to NEEM, where 2008 mobility was around 7 bladders per Case Quadtrac and a per-Case performance of 8–10 is needed to breakeven.

GrIT10 achieved the needed performance. Analyses based on average sled-train resistance and temperature-dependent bladder-sled resistance confirm that the Case in 2010 trim can tow eight bladders (four dual-bladder sleds) with substantial reserve capacity. A performance of 10 bladders per Case is within reach by using black bladders, rather than less efficient black covers, to increase solar gain at low air temperatures. Interestingly, GrIT's 8–10 bladder tractor capacity is identical to the current load limit for SPoT. Warmer air in Greenland compensates for weaker snow conditions to yield the same seasonal load limits.

Besides breaking even economically, other factors make GrIT an attractive alternative to aircraft resupply in Greenland: low emissions, reduced fuel consumption, out-size cargo capability, science opportunities along the route, and hedge against LC130 cost increases.

GrIT11 will use two lighter Case Quadtracs with the same 485-hp engines and 36-in.-wide tracks as the GrIT10 Case. Ground pressure will be lower, which should significantly decrease rut depths and self-propulsion resistance. As with sled improvements, this benefit can be self-reinforcing: the tractors should develop more drawbar power, which allows higher towing speeds, which increases frictional heating, which lowers sled resistance. However, lower tractor weight could reduce maximum drawbar pull. Thus, the GrIT11 tractors should be monitored to determine whether lower ground pressure or higher weight provides optimum towing capacity for Greenland snow conditions. Ballast weights can be added if necessary.

8 Recommendations

We make the following recommendations for GrIT based on this work:

- Acquire black fuel bladders to increase passive solar heating and thereby reduce bladder-sled towing resistance. This will increase load limits or create reserve tractor capacity.
- Set the GrIT11 load limit equivalent to seven bladders per Case Quadtrac (six 3000-gal. fuel bladders and a new air-pillow cargo sled on four sheets of HMW-PE). This limit recognizes that the GrIT11 Quadtracs are lighter than their GrIT10 counterpart and the air-pillow cargo sled is untested.
- Set the GrIT11 Case Magnum load limit equivalent to five fuel bladders.
- Install automated mobility instrumentation in the GrIT11 tractors to help assess season performance of the new tractors and sleds. Complement the mobility data with crew-acquired Rammsonde snow-strength profiles and field notes along the route.
- Plan to shuttle half-loads up the 60-mile transition onto the main ice sheet. This strategy worked well during 2010 to reduce frustrating and time-consuming immobilizations.
- In 2011, use the 2010 route alignment for outbound travel from NEEM to Summit and the 2008 route alignment for return travel Summit to NEEM. Conduct Rammsonde profiles along both routes and compare snow-strength and mobility data to assess whether 2010 alignment offers better fleet mobility.
- Assess the performance of the lighter GrIT11 Quadtracs to determine whether lower ground pressure or higher weight optimizes towing capacity for Greenland conditions.

References

Bäurle, L., U. Kaempfer, D. Szabó, and N.D. Spencer. 2007. Sliding friction of polyethylene on snow and ice: Contact area and modeling. *Cold Regions Science and Technology* 47: 276–289.

Colbeck, S.C. 1992. *A review of the processes that control snow friction*. CRREL Report 92-2. Cold Regions Research and Engineering Laboratory.

Kaempfer, T.U., and J.H. Lever. 2009. Snow-sled frictional modeling for the Greenland and Antarctic Inland Traverses (GrIT, SPoT), Interim report. Letter Report to National Science Foundation, Office of Polar Programs, 23 Oct 2009. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Lever, J.H. 2009. Mobility support for South Pole Traverse. Field Report to National Science Foundation, Office of Polar Programs, 4 Nov 2009. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Lever, J.H. (2010a) Lightweight cargo sled for SPoT10-11 refrigeration module: Design & construction details, Letter Report to National Science Foundation, Office of Polar Programs, 18 Aug 2010. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Lever, J.H. (2010b) Lightweight cargo sleds for GrIT11: design details, Letter Report to National Science Foundation, Office of Polar Programs, 26 Aug 2010. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Lever, J.H., and G. Gooch. 2010. Lightweight cargo sled for polar heavy traverses: Concept development, laboratory tests & design implications, Letter Report to National Science Foundation, Office of Polar Programs, 5 Aug 2010. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Lever, J.H., and J.C. Weale. 2007. Feasibility of overland traverse to re-supply Summit Camp: Fleet configuration and economic analysis. Letter Report to National Science Foundation, Office of Polar Programs, 14 December 2007. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Lever, J.H., and J.C. Weale. 2009. Mobility and economic feasibility of the Greenland Inland Traverse (GrIT). Letter Report to National Science Foundation, Office of Polar Programs, 4 June 2009. U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Lever, J.H., J.C. Weale, R.G. Alger, and G.L. Blaisdell. 2004. Mobility of cargo trains during Year Two of the proof-of-concept South Pole traverse. ERDC/CRREL Technical Report TR-04-22.

Lever, J.H., J.C. Weale, R.G. Alger, G.L. Blaisdell, and J.H. Wright. 2006. Mobility solutions for the South Pole traverse tractor-sled trains. In *Proceedings of the 10th European Conference of the International Society for Terrain-Vehicle Systems (ISTVS), Budapest, Hungary* (CD-ROM).

Mercer, J.L., J. Lever, S. Newman, E. Deeb, B. Tracy, J. Weale, A. Delaney, R. Davies, and K. Emery. 2010. Crevasse detection and avoidance for safe traversing on the dynamic and annually changing margin of the Greenland Ice Cap, abstract. In *Proceedings of American Geophysical Union Fall Meeting, December 2010, San Francisco, CA*.

Weale, J., and J.H. Lever. 2008. Innovations in over-snow cargo transport. *Cold Regions Science and Technology* 52: 166–176.

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14. ABSTRACT

The National Science Foundation initiated the Greenland Inland Traverse (GrIT) to resupply science stations at NEEM and Summit via over-snow transport. The inaugural traverse in 2008, while successful, encountered mobility problems owing to steep slopes along the first 60 miles, soft snow along much of the route, and higher than expected towing resistance of the fuel sleds. With our guidance, GrIT implemented several changes to improve performance in 2010, and these changes were largely successful. Planned half-load shuttling reduced immobilizations on steep sections, omission of the steel fuel sled eliminated the worst-performing sled, and towing the fuel bladders two inline on long plastic sheets rather singly on separate sheets improved performance of the remaining fuel sleds. In addition, we instrumented the bladder sleds to quantify the expected dependence of towing resistance on sled–snow interface temperature. Sliding friction warms the sled and produces a thin meltwater layer that decreases towing resistance over cold snow. Furthermore, to assess benefits of artificially warming the sleds, one dual-bladder sled included electric heating blankets (optionally on or off) and the other included black wrappers to increase solar gain. This report summarizes GrIT10 performance, evaluates the changes implemented and assesses implications for future GrIT operations.

15. SUBJECT TERMS

Greenland Inland Traverse (GrIT)	NEEM	Sliding friction
GrIT10 performance	Over-snow transport	Summit Station
	Plastic sheets	Towing fuel bladders

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