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Mobility and Economic Feasibility of the Greenland Inland Traverse (GrIT)

James H. Lever and Jason C. Weale,

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Final report

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Abstract: The mobility and economic feasibility of resupplying Summit Camp on the Greenland ice cap from Thule AFB via a 1410-mile (round trip) overland traverse was examined following safe and successful implementation of the Greenland Inland Traverse (GrIT) proof-of-concept in 2008. The mobility and economic assessments focused on delivery capabilities for a tractor fleet consisting of two prime movers and one fleet-support vehicle and its economics compared with re-supply by LC130 aircraft. The mobility feasibility was based on tractor drawbar and sled resistance measurements collected during the GrIT08 proof-of-concept. Sled resistance measurements indicate GrIT will recover its capital investment and operating costs with a mobility performance of eight 3000-gal. fuel bladders towed per prime mover given a 20% increase in LC130 hourly costs. This mobility level is likely, provided GrIT systematically improves bladder-sled performance (currently six bladders per prime mover) through incremental improvements like the use of black fuel bladders and black HMW-PE sleds. As argued in our previous work, an overland traverse represents an economic buffer against unconstrained and likely LC130 SAAM hourly rate increases. It is recommended that GrIT acquire two prime movers with 36-in. wide tracks (70,000 lb each with a drawbar pull of 21,000 lb) and a lighter-weight fleet-support vehicle with 4100 lb of drawbar pull. Loads should be shuttled up the 60-mile transition onto the main ice sheet to eliminate frustrating and time-consuming immobilizations caused by weak snow and steep grades. Additional improvements, such as the development of a lightweight cargo sled, a snow-properties database, and fleet performance analysis tools should be developed in partnership with the South Pole Traverse (SPoT).

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Preface

This study was conducted for the National Science Foundation, Office of Polar Programs (OPP).

The work was performed by Dr. James H. Lever and Jason C. Weale of the Force Projection and Sustainment Branch (CEERD-RR-H), Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL).

It is essential to acknowledge the tireless efforts of the GrIT team during 2008 and 2009 to bring this project to reality over so short a time: Jay Burnside, Brad Johnson, Larry Levine, Allen O'Bannon, Pat Smith, Susan Zager, Eric Nichols and many others.

The authors also thank Larry Levine for providing weight information and onboard performance data on the Case. They sincerely thank Pat Haggerty and Renee Crain at NSF/OPP-ARC for their enthusiastic support of GrIT.

This report was prepared under the general supervision of James Buska, Branch Chief, FSSB, CRREL; Dr. Justin B. Berman, Chief, Research and Engineering Division, CRREL; Dr. Lance D. Hansen, Deputy Director, CRREL; and Dr. Robert E. Davis Director, CRREL. The Commander and Executive Director of the ERDC is Colonel Kevin Wilson. The Director is Dr. Jeffrey Holland.

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
miles per hour	0.44704	meters per second
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms

Executive Summary

In 2008, the National Science Foundation's Office of Polar Programs (OPP) initiated a 705-mile (1410-mile round trip) over-snow traverse, departing from Thule Air Base, to re-supply the international drilling camp at NEEM and Summit Station at the height of the Greenland ice sheet. Note that the actual distance, once traversed, was 705 miles one way compared to 600 miles noted in Lever and Weale (2011). This inaugural Greenland Inland Traverse (GrIT) used tractors and sleds similar to those employed by the South Pole Traverse (SPoT) and successfully established a safe route onto the ice sheet and delivered fuel to both NEEM and Summit. Mobility data from GrIT08 indicated that the Case Quadtrac tractor developed drawbar pull (*DBP*) close to that expected, but that the fuel sleds, especially the steel tank sled, towed worse than expected, based on SPoT experience. GrIT, therefore, conducted tests on the ice-transition near Thule in March 2009 in hopes to find simple improvements to its mobility problems.

Mobility data obtained from NEEM during GrIT08, from SPoT in 2008–09, from Quebec in February 2009, and from the transition near Thule in March 2009 have not identified a towing tractor clearly superior to the Case Quadtrac for use on GrIT. A well-balanced Case weighing about 70,000 lb and fitted with 36-in.-wide tracks should reliably achieve *DBP* = 21,000 lb and develop lower self-propulsion losses compared with the Case in GrIT08 trim (narrower tracks and less well balanced). The tractor is designed to pull hard day-in and day-out, and its articulated steering is an advantage when pulling at high drawbar loads compared with two-track vehicles. The Case should be adequate for GrIT to be economically attractive compared with aircraft re-supply of NEEM and Summit. Furthermore, the 2009 tests confirmed that the Tucker Sno-Cat can reliably develop towing forces of 4100 lb at 8 mph, sufficient for it to tow crew accommodations and all fleet supplies except fuel.

Steep slopes along the 60-mile transition onto the main ice sheet were a primary cause of immobilization during GrIT08. Nevertheless, the level-snow towing resistance per unit weight, T/W, of high molecular weight polyethylene (HMW-PE) sleds during GrIT08 was higher than expected: T/W averaged 0.13 for bladder sleds through the transition to just past

NEEM; coupled HMW bladder and cargo sleds the averaged $T/W = 0.16$ for the last 350 miles to Summit. On the weakest snow of the SPoT route, the plateau swamp, HMW bladder sleds averaged slightly better, $T/W = 0.11$ in steady-state towing. However, these SPoT sleds displayed higher startup resistance for 20–50 minutes that is probably related to the energy needed to warm up the undersides of the sleds sufficiently to produce a lubricating water film. It is possible that the GrIT sleds never achieved this warm-up condition. If true, black HMW sleds and black bladder-containment envelopes would reduce sled friction by increasing solar warming of the sled. Current performance of the GrIT bladder sleds indicates that each Case can tow about seven 3000-gal. bladders from the transition to NEEM and about six bladders thereafter to Summit. Note that the steel-tank sled was much less efficient: one 3000-gal tank sled requires the same towing effort as four 3000-gal. bladders on HMW sleds.

We examined the long-term economic feasibility of GrIT based on a three-vehicle fleet (two Case towing tractors and one Tucker support vehicle) re-supplying NEEM and Summit via a single round-trip per year. We varied the number of bladder or cargo sleds towed per Case to identify the mobility performance needed for GrIT to break even economically. Benefits 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. At the 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 increase 20% to $8200/hr, GrIT would break even at a performance of eight bladders per Case.

As it currently operates, GrIT is close to achieving the needed performance. The critical route segment is from just past the transition to NEEM, a distance of about 230 miles, where current performance is about seven bladders per Case and a performance of 8–10 is needed. GrIT can implement half-load shuttling along the 60-mile transition to reduce immobilizations from steep slopes; after re-supplying NEEM, GrIT would only need to tow four–six bladders per Case across 410 miles to Summit, a performance level it has already demonstrated. Note that positive feedback is likely with sled improvements: lower towing resistance allows higher towing speeds, which increases frictional heating of the sleds, which lowers resistance even further. That is, the risk to commit to a three-vehicle traverse is small and can be mitigated with a modest sled-development effort.

Our economic analysis probably understates the program-wide benefits of GrIT. Other potentially significant benefits could include:

- Cost savings possible by shipping cargo to Thule rather than flying it to Kanger.
- Cost savings possible by pre-fabricating buildings and towing them to Summit rather than building them at Summit from components.
- The scientific value of significantly reduced air emissions realizable by traversing cargo to Summit rather than flying it there.
- The value of the traverse to establish and remove large science camps elsewhere in Greenland compared with building skiways and flying in and out all camp infrastructure.
- Operational cost savings at Kanger for large numbers of LC130 flights offset.
- The traverse as a hedge against unrestrained LC130 costs (SAMM rate and major aircraft overhauls).

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

- Acquire two Case Quadtrac tractors with 36-in.-wide tracks as its primary towing vehicles. We know of no other vehicles with superior demonstrated performance over polar snow fields for comparable costs.
- Acquire a Tucker SnoCat as a fleet-support vehicle and GPR platform. The Tucker will perform well in both capacities, serving to verify a safe route through the transition and towing accommodations and fleet supplies.
- Implement, in partnership with SPoT, a systematic program to improve the performance of fuel-bladder sleds. In the near term, this should include lab tests and field trials of black HMW-PE sleds, black bladder-containment envelopes, and in-line towing of two 3000-gal bladders on the same sled. Field monitoring of towing forces, sled temperatures, and tractor performance should be an integral part of this effort.
- Tow fuel only in bladders on flexible sleds and acquire the pumping system needed for efficient daily fueling from bladders. This will elimi-

nate the need to tow an inefficient and expensive tank sled for daily fueling.

- Develop, in partnership with SPoT, a lightweight cargo sled that interfaces a stiff deck with a flexible HMW sled. Tare weight should be less than 5000 lb for a 20,000-lb cargo capacity, with ground pressure close to 1 psi. This sled would present a more conventional arrangement for securing cargo while retaining the low towing resistance of simple HMW cargo sleds.
- Plan to shuttle half-loads up the 60-mile transition from Thule onto the main ice sheet. This would eliminate frustrating and time-consuming random immobilizations and add little if any time to cross the transition. A convenient arrangement would be four bladders per spreader with two bladders in-line on HMW sheets attached to the ends of the spreader. This arrangement would permit easy connections for four or eight bladders per Case and allow the sleds to straddle the tractor ruts to minimized snow-compaction losses along those ruts.
- Develop, in partnership with SPoT, the snow-properties database and analysis tools needed accurately to model and predict sled and tractor performance. Positive feedback for incremental sled or tractor improvements, through increased travel speeds and sled warming, will amplify performance improvements. By coupling a good predictive model with an economic assessment, it will be possible to pursue development ideas most likely to payback for GrIT.

1 Introduction

The National Science Foundation’s Office of Polar Programs (OPP) operates year-round science stations on the ice sheets of Antarctica and Greenland. Until recently, South Pole Station was re-supplied entirely via LC130 ski-equipped aircraft from McMurdo Station on the Antarctic coast. Beginning in 2002, OPP initiated development of a South Pole Traverse (SPoT) to deliver fuel and cargo 1030 miles (one way) over snow to South Pole using a fleet of tractors pulling specially designed sleds. In 2008–09, SPoT completed the first major over-snow re-supply of South Pole. It delivered 805,000 lb of fuel (115,000 gal.) and 129,000 lb of cargo to South Pole, returning 177,000 lb of waste from South Pole to McMurdo. This traverse, consisting of eight towing tractors and a radar vehicle, offset 36 LC130 flights and saved 88,000 gal. of fuel in the process. Lightweight, flexible fuel and cargo sleds, developed in partnership with CRREL, enabled SPoT to achieve this high delivery efficiency.

In 2008, OPP initiated a 705-mile (one-way) over-snow traverse to resupply Summit Station, at the height of the Greenland ice sheet, from Thule Air Base (Fig. 1). CRREL provided technical assistance for this Greenland Inland Traverse (GrIT) and advised starting with similar tractor and sled technology as used in Antarctica. A feasibility study for GrIT showed favorable benefit/cost provided the tractors and sleds performed only slightly (20%) less efficiently than their Antarctic counterparts (Lever and Weale 2007). CRREL also processed satellite imagery and provided radar expertise to establish a route to avoid crevasses over the 60-mile transition from the ice edge near Thule onto the main ice sheet.

The inaugural GrIT, conducted in May–June 2008, successfully negotiated a crevasse-free route onto the ice sheet and delivered more than 4000 gal. of fuel to the international drilling camp at NEEM and 2000 gal. to Summit Station. This proof-of-concept fleet consisted of one towing tractor and one radar/support vehicle. Unfortunately, the fleet was unable to achieve performance comparable to SPoT over long stretches of snow that was weaker than that found along the Antarctic route. This performance raised doubts about the long-term economic feasibility of GrIT. Consequently, mobility tests were undertaken in March 2009 on the ice-sheet transition near Thule to seek improved tractor and sled performance via small changes to these systems.

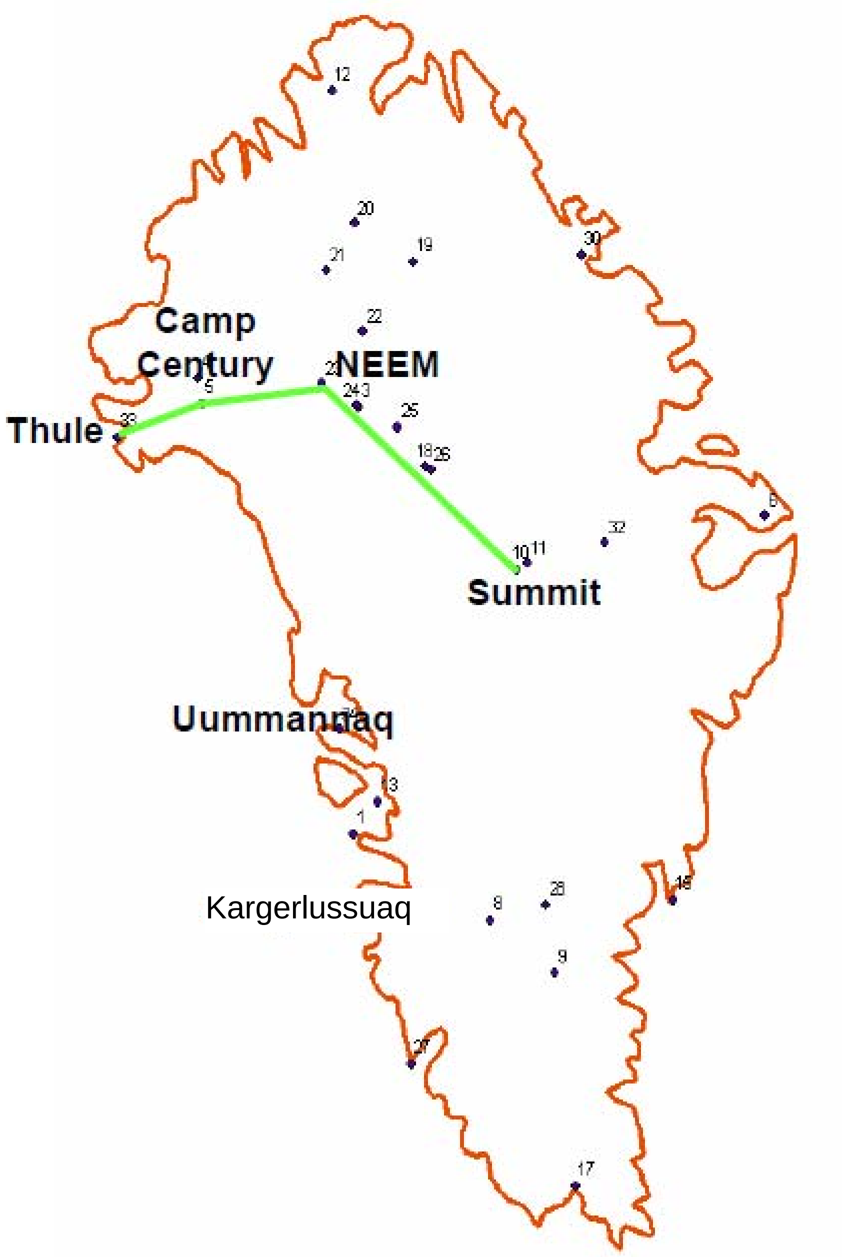

Figure 1. Schematic of the 705-mile (1410-mile round trip) GrIT08 route across the Greenland ice sheet. The transition onto the main ice sheet covered about 60 miles (about half the distance to Camp Century) and included numerous deviations to avoid crevasses. The 570 miles from Camp Century through NEEM to Summit Station had negligible slopes but consisted of soft snow.

This report summarizes the mobility performance of the GrIT08 tractor and sleds and the 2009 tests, and compares the results with performance achieved during SPoT08-09. It then presents a revised feasibility assessment for GrIT based on current performance and costs. It identifies performance and cost targets that must be attained for GrIT to achieve a favorable benefit/cost result and describes approaches to achieve them.

2 GrIT08 Fleet

The GrIT08 fleet consisted of two vehicles: a Case Quadtrac towing tractor and a Tucker SnoCat support vehicle that also served as the ground-penetrating radar (GPR) platform. The fleet departed the Thule ice edge on 21 May with the Case responsible for towing the heavy sleds: four flexible bladder sleds and one steel tank, each carrying 3000 gal. (21,000 lb) of fuel, and two flexible cargo sleds carrying a total of about 25,000 lb of tools and supplies (Fig. 2). The bladder and cargo sleds were on separate ski-supported spreader bars. Total gross weight of the heavy-sled train, including spreaders, was about 154,000 lb. The Tucker towed a wannagan (an insulated tent on a sled) and three lightweight sleds carrying tools and supplies (Fig. 3).

Figure 2. 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.

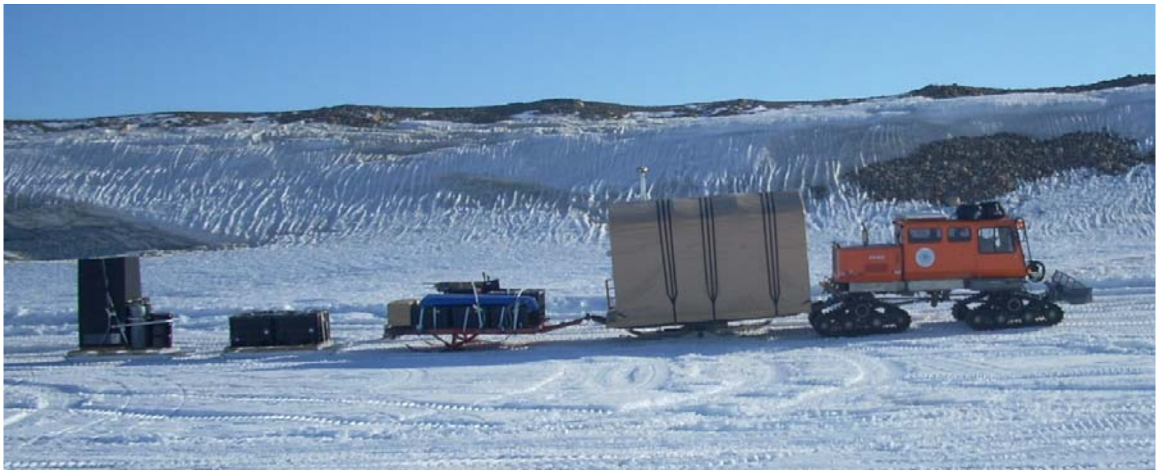

Figure 3. Tucker SnoCat towing wannigan and support sleds up the ice-sheet transition.

The Case Quadtrac was a 485-hp, four-track-drive tractor with articulated steering. It weighed about 64,000 lb with snow blade, three-point hitch, fuel and operator, and produced average ground pressure of 7.3 psi. This tractor was very similar to the four Quadtrac tractors used during SPoT 08-09.

The Tucker SnoCat was a 140-hp, four-track-drive tractor with articulated steering. It weighed about 14,600 lb with blade, fuel, operator and radar operator, and produced an average ground pressure of about 1.8 psi. It was normally fitted with a GPR antenna on a long boom (Fig. 4) to detect hidden crevasses along the route.

Figure 4. Tucker fitted with GPR antenna (inside inner tube) at the end of an aluminum boom.

Figure 5. Four bladder sleds connected behind a spreader bar. Each sled consists of a 3000-gal. fuel bladder strapped to a flexible sheet of HMW-PE.

The bladder sleds each consisted of a 3000-gal. transportable fuel bladder strapped to a 8-ft-wide × 34-ft-long × ½-in.-thick sheet of high molecular weight polyethylene (HMW-PE, Fig. 5). These sleds and their steel tow plates were similar to those trialed on the Ross Ice Shelf during SPoT 07-08, with continuous extruded HMW-PE substituted for welded sheets of ultra-high molecular weight polyethylene (UHMW-PE). This change was made to avoid UHMW-PE weld failures experienced during SPoT 07-08. GrIT08 was the first field application of HMW sleds following laboratory tests at CRREL in early 2008. SPoT subsequently used all HMW sleds for its successful 2008–09 season.

The GrIT08 flexible cargo sleds used the same HMW sleds and tow plates as the bladder sleds, with boxes, pallets and bulk cargo strapped directly to the sheets (Fig. 6). GrIT08 was the first field application of a flexible cargo sled, following successful testing at CRREL in early 2008. SPoT employed similar flexible cargo sleds for the first time in Antarctica during the 2008–09 season.

Figure 6. Two flexible cargo sleds, each consisting of boxes, pallets or bulk cargo strapped directly to a flexible sheet of HMW-PE.

The Case was fitted with an instrumented load pin (50,000-lb capacity) to measure the drawbar force required to tow the sleds during normal operations. A datalogger measured drawbar forces at 1 Hz and logged average force and standard deviation every minute, along with tractor speed and position determined via global-positioning system (GPS). We obtained route elevation data from separate GPS units.

3 GrIT08 Predicted Performance

The feasibility study submitted prior to the 2008 GrIT season (Lever and Weale 2007) included performance predictions for Case Quadtrac tractors pulling each sled type used during GrIT08. The performance data were derived from at least 2 years of drawbar and bladder-sled tests near McMurdo Station and fuel-tank towing resistance along the Ross Ice Shelf. The authors applied two "de-rating" factors to allow for unknown but expected weaker snow conditions along the Greenland ice sheet: tractor drawbar pull was reduced by 20% and sled towing resistance was increased by 20%. The resulting estimates were for level snow, a condition expected for more than 90% of the route.

The feasibility study assumed use of Quadtrac STX530 tractors with gross weights of 69,000 lb and predicted maximum drawbar pull (*DBP*) of 21,000 lb in Greenland. For the lighter GrIT08 Quadtrac, we would have predicted $DBP \approx$ 19,000 lb. Our customary metric for sled towing resistance, T, is the sum of average resistance, R, plus 3 standard deviations, σ_R. This recognizes that variations in snow strength over 10–30 m (30−90 ft) scales produce resistance peaks that the tractor must overcome to avoid immobilization. With de-rating factors, predicted towing resistances for the GrIT08 sleds would be 1800 lb per bladder sled or 7200 lb for the group of four bladders sleds, 3300 lb for the pair or cargo sleds and 4000 lb for the full fuel tank. That is, predicted total resistance for the GrIT08 heavy sleds on level snow would be 14,500 lb based on pre-departure knowledge. This value is well below the predicted *DBP* of the tractor.

It is often helpful to characterize the towing efficiency of a sled as the towing resistance per unit weight or resistance coefficient, T/W, where W is sled weight (tare weight included). The predicted resistance coefficients for the heavy sleds in Greenland were 0.082 for the bladders sleds, 0.11 for the cargo sleds, and 0.12 for the fuel-tank sled. Note that only the tank sled has appreciable tare weight (12,400 lb) compared with its total sled weight (33,400 lb).

4 GrIT08 Mobility

4.1 Overview

Figure 7 shows GrIT08 daily advance plotted against route location. The fleet required 16 days to travel 66 miles through the transition zone to waypoint B11D, including 7 days with no advance owing to poor weather and crevasse surveys. Mobility then improved, and the fleet covered the remaining 639 miles to Summit in 19 days, including 2 weather days and 1 day stationary at NEEM.

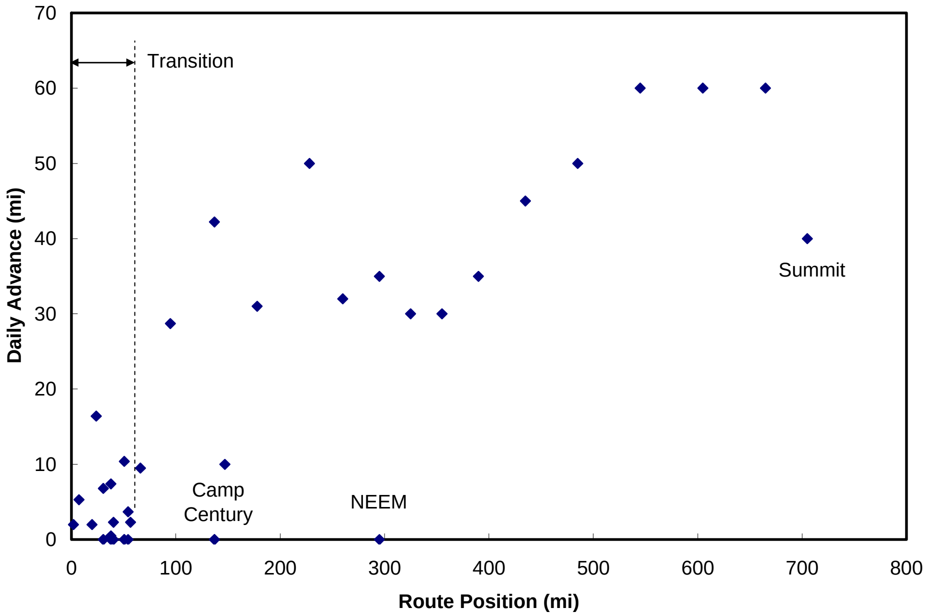

Figure 7. Daily advance plotted against route position. Steep uphill slopes were the main cause of poor mobility through the transition zone to the main ice sheet.

The Case immediately encountered mobility problems along the approximately 60-mile transition onto the ice sheet. Steep slopes caused numerous immobilizations, with soft snow and side slopes playing aggravating roles. Uphill slopes of 5–7% occurred at several locations and 2–3% slopes were common. A 5% slope reduces the available DBP of the tractor by about 5% of its weight or 3200 lb. More significantly, it increases the towing resistance of the 154,000-lb sled train by 7700 lb. That is, the tractor can only tow about half of the sleds up such slopes and thus must disconnect and shuttle them as smaller trains. On short 7% slopes near B9 and

B10 waypoints, the Case needed to track-pack the trail before being able to pull the four bladders uphill (91,000 lb with spreader). Soft snow combined with uphill grades also made shuttling necessary on shallower slopes. As a result, the Case was only able to tow all the heavy sleds as a single train for short distances along the transition.

Side-slopes initially caused concern about bladder-sled stability, especially when combined with downhill grades. The GrIT08 crew initially used the Tucker to hold-back and thus stabilize the bladder sleds down the steeper hills. As the team gained experience, this technique was not needed, although the Tucker was often standing by to assist.

Past the transition, uphill slopes were generally below 1% and steadily diminished to less than 0.4% by NEEM. Beyond NEEM, slopes were negligible. Except for two short 1.6 and 2.5% climbs, the Case was able to pull all the heavy sleds in a single train from B11D to Camp Century, covering the 71 miles in 2 long days. It also pulled all sleds together from just past Camp Century almost to NEEM, covering that 138 miles in 4 days. Unfortunately, the snow became much softer just before NEEM, and the Case slowed to a crawl. The operator (B. Johnson) was forced to shuttle the four bladders and the tank-cargo sleds as separate trains into NEEM.

The team delivered one full fuel-bladder sled to NEEM before heading on towards Summit. Unfortunately the Case was unable to tow the nearly empty fuel tank, two cargo sleds and three remaining bladder sleds as a single train much beyond the boundary of NEEM. After 2 days of shuttling, covering 60 miles, the crew cached the empty fuel tank. The Case then completed the 350-mile trip to Summit in 7 days, towing all remaining sleds in a single train. Note that they cached a full bladder sled, for the return trip, after the second day and consumed fuel from the remaining two bladders.

4.2 Case Traction and Power

Although no formal drawbar tests were conducted during GrIT08, measured towing forces allow us to document the performance of the Case. Figure 8 shows the measured drawbar pull and drawbar power (product of *DBP* and ground speed) versus route position. The *DBP* values are 1-minute average towing forces ($T = R + 3\sigma_R$) developed without breaking traction. That is they represent minimum usable *DBP* at 3–6 mph. Drawbar power is the productive power used to move the sleds. It is the net power available from the tractor after deducting internal losses (engine and transmission friction, track-turning losses) and self-propulsion losses through the snow (snow compaction and slip). Mobility of the sled train can be limited by available traction or power. When traction limited (e.g., climbing hills), the tractor can't overcome sled resistance and becomes immobilized. When power limited, the tractor can pull the sleds but its forward speed is limited. There can be some interplay between the two conditions: at low power-limited speeds, the tractor–sled train may not have sufficient momentum to carry through locally weak snow and may become immobilized.

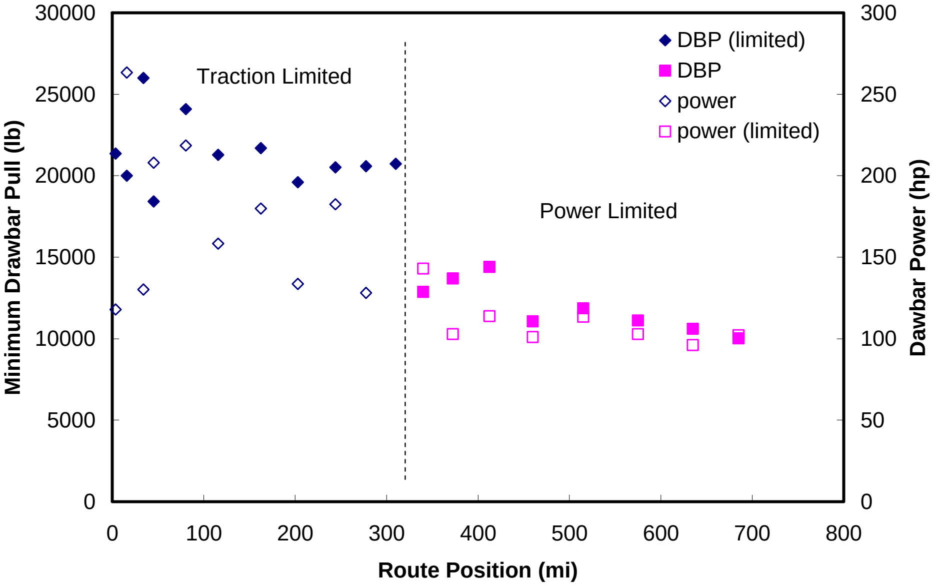

Figure 8. Case drawbar pull (solid symbols) and drawbar power (open symbols) versus route position. Initially, available traction limited drawbar pull and often necessitated shuttling. After NEEM, required *DBP* was lower and power limited the rate of advance.

The Case was traction limited to just past NEEM as it pulled all the sleds in a single train or shuttled partial trains up steep slopes. The *DBP* values obtained through this region averaged 21,000 ± 2000 lb (± 1σ). This compares favorably with the predicted Case *DBP* of 19,000 lb based on derated Antarctic performance. After delivering a bladder to NEEM and caching the empty tank sled, required DBP dropped and the Case became power limited. Drawbar power averaged 110 ± 10 hp. This is less than ¼ of the rated power of the engine. Drawbar power in the traction-limited region was higher but more variable, 170 ± 50 hp.

The rut depths made by the Case were generally noted once or twice per day. They differed little between the traction-limited and power-limited regions, 10 ± 2 in. versus 12 ± 2 in., respectively. Nevertheless, this difference could be important relative to the 16-in. ground clearance of the Case: the tractor dragged its hitch (and thus its belly pan) at times through the power-limited region past NEEM. Also, higher track slip usually accompanies deeper sinkage, which in turn increases self-propulsion losses.

The crew (notably J. Lever) did not conduct sufficient snow-strength measurements to correlate strength with *DBP* along the transition. It undoubtedly played a role in causing immobilizations, although probably not as dominant as that of the steep slopes. Snow strength, as characterized by the energy needed for the Rammsonde probe to penetrate 60 cm (24 in.) into the snow, $E60$, averaged 150 ± 80 J in the traction-limited region compared with 70 ± 20 J in the power-limited region. These are low snow strengths generally: measurements along the Antarctic plateau snow-swamp averaged 150 ± 10 J, by far the weakest snow along the SPoT route.

4.3 Sled Resistance

The main GrIT08 mobility dataset consists of approximately 200 hours of measured Case towing forces, ground speeds, locations, and elevations. These provide extensive sled-resistance data for operational towing along the entire route. The sleds were towed in limited configurations. Before NEEM, the configurations were four bladder sleds on a spreader, the fuel tank, and two cargo sleds on a spreader, and both of these groups as a single train. After NEEM, only three bladders remained on the spreader and the two groups were shuttled until the empty tank was cached (mile 355). Then, the remaining HMW-PE sleds, still on two spreaders, were towed as a single train.

Towing resistance per unit weight, T/W, is an efficiency measure that allows us to compare these various configurations. Figure 9 shows the average value of T/W versus average route position for each available configuration. We corrected the resistance values for slopes to determine effective resistance across level snow at the same locations. Some limitations are inherent in the dataset. Separate shuttling of the bladder sleds provided many measurements of their towing resistance until mile 355, after which the bladders and cargo sleds were towed as a single train. Furthermore, the cargo and tank sleds were never separately towed before mile 355. This makes it difficult to discern whether the bladder and cargo sleds have similar towing coefficients despite their different ground pressures. Also, the tank–sled resistance coefficient must be estimated on the basis of the higher resistance of the tank–cargo group compared with the bladder sleds over the same terrain, assuming that the bladder and cargo sleds do indeed have similar resistance coefficients.

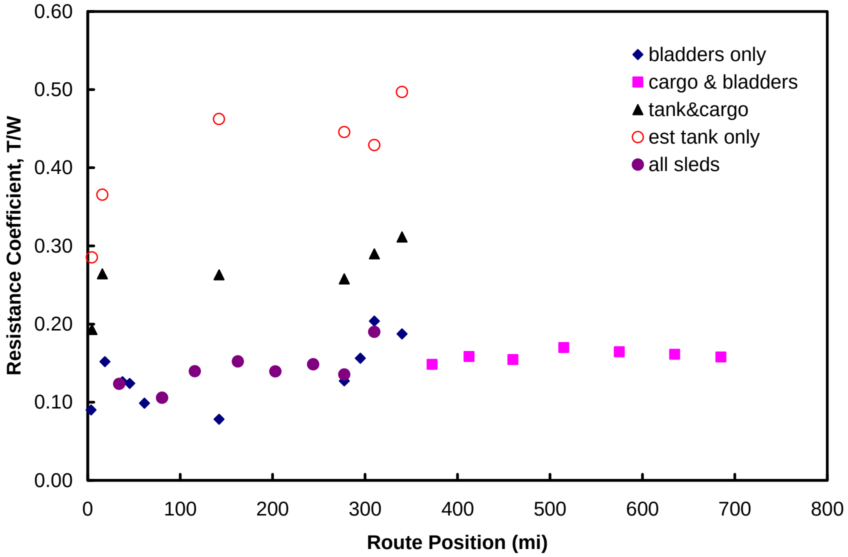

Figure 9. Sled resistance coefficient versus route position. The solid symbols are direct measurements while the open symbols are estimates for the fuel tank.

The bladder sleds averaged $T/W = 0.13 \pm 0.04$, with slightly lower values along the transition (0.12 ± 0.2) compared with near NEEM (0.17 ± 0.03). The lowest value of $T/W = 0.078$ occurred as the bladders were towed for 10 miles out of Camp Century. After mile 355, the combined bladder and cargo sleds averaged $T/W = 0.16 \pm 0.01$. This is similar to that for the bladders near NEEM, the closest area for comparison. Because the bladders constituted 40–70% of the combined weight, they should have governed the resistance of this group. Thus, the measured resistance of the bladder sleds for the majority of the route is twice as high as that predicted based on pre-departure Antarctic data ($T/W = 0.082$).

At this point, we have no evidence to suggest that the bladder and cargo sleds have different resistance coefficients, about $T/W = 0.16$ across most of the route. We predicted $T/\mathrm{W} = 0.11$ for the cargo sleds because we had no data for cargo sleds and assumed that they would tow slightly harder than bladders sleds.

The resistance coefficients obtained when towing all sleds together, measured on several occasions from the transition to just past NEEM, are similar to those measured for bladder sleds only and for bladder–cargo combinations, $T/W = 0.15 \pm 0.02$. This is reasonable, given that the train weight was dominated by the bladder and cargo sled weights.

The tank–cargo sled combination was shuttled on several occasions to mile 355 (Fig. 9). The average resistance coefficient, $T/W = 0.26 \pm 0.04$, was much higher than that of bladder or bladder–cargo sled combinations. The fuel tank often dragged its saddle when towed in-line with the tractor (and hence towed in the tractor's ruts, Fig. 2). Approaching NEEM, the crew switched the tank location to the end of the spreader, counterbalanced by the two cargo sleds at the other end. Although the saddle rarely dragged in this location, the data show no appreciable reduction in towing resistance.

Given that the tank was half or less of the tank-cargo train weight, its individual resistance coefficient must have been much higher. We may estimate the tank resistance from the tank–cargo data by assuming that the cargo sleds had the same coefficients as the bladders over the same terrain. This yields $T/W = 0.41 \pm 0.08$ as the average for the tank sled. To make matters worse, fueling decreased the volume in the tank with distance. If we correct for this effect, the *DBP* needed to tow a full 3000-gal. fuel tank would have increased from approximately 9500 lb near the transition to approximately 17,000 lb just past NEEM. These are essentially the same values needed to tow four full fuel bladders over the same terrain.

5 March 2009 Mobility Tests

GrIT did not operate a traverse to Summit in 2009. It did, however, conduct mobility tests on the transition near Thule to seek insight into causes and possible solutions for the poor mobility experienced during GrIT08. Formal drawbar tests were conducted on the Case in several configurations, a UHMW-PE bladder sled and a new spreader bar were tested, and towing performance of the Tucker was assessed. Limitations with available equipment and test sites constrained these tests, but they nevertheless produced some helpful results.

5.1 Case Drawbar and Self-Propulsion Tests

Tractor drawbar pull should increase for increased weight at the same ground pressure or decreased ground pressure for the same weight. Of the two approaches, decreasing ground pressure brings the added benefit of reducing sinkage and hence self-propulsion losses. Both *DBP* and sinkage should be optimal when the front/rear weight distribution is nearly equal under towing forces, corresponding to approximately 55/45 static weight distribution. A set of 36-in.-wide tracks were obtained for the Case to replace the standard 30-in.-wide tracks and thus decrease average ground pressure by 20%. Drawbar test were conducted to assess this change and effects of gross weight and weight distribution. Our usual DBP measure consists of 1-s maximum forces achieved prior to breaking traction, with the average reported for four–five consecutive pulls over level ground.

The load vehicle available for the drawbar tests was a Caterpillar 931 tracked loader (about 30,000 lb gross weight). It could only bring the Case to a halt by locking its tracks and burying its bucket into the snow (Fig. 10). Even so, the Case could drag the 931 many feet (even hundreds of feet) before breaking traction. Local variations in snow strength thereby influenced the test results. In each configuration, the tests usually consisted of two sets of five pulls and immobilizations, outbound and inbound, to average any slope effects. After each test series, the Case usually drove alone (i.e., not towing) adjacent to the test site for about 15 minutes to provide data on self-propelled rut depth, power, and fuel consumption. Table 1 summarizes the results. Drawbar coefficient, *DBP*/*W*, helps to compare different configurations.

Date	Configuration	Comments	Track Width	Gross Weight	Front	Rear	Average Ground Pressure	DBP	DBP/W	Self-Prop Rut Depth	Self-Prop Power	Self-Prop Fuel	Snow Strength E60
			(in.)	(lb)	(%)	(%)	(psi)	(lb.)		(in.)	(%)	(gal./mi)	(J)
3/14	Blade, no weights, as driven grit08	Load pin failed, data unreliable	30	63,500	63	37	7.2						
3/20	No blade, no weights	Rough snow, high variability	36	57,800	55	45	5.5	16,500 ± 2,700	0.28 ± 0.05	6 ± 2	40 ± 5	2.3 ± 0.4	100 ± 20
3/21	No blade, no weights	Repeat in uniform snow	36	57,800	55	45	5.5	13,200 ± 500	0.23 ± 0.01	6 ± 2	45 ± 3	2.6 ± 0.2	90 ± 20
	No blade, rear ballast	Uniform snow	36	64,400	42	58	6.1	13,300 ± 1,100	0.21 ± 0.02	7 ± 2	48 ± 3	2.7 ± 0.2	90 ± 20
3/24	Blade, no weights, as driven grit08	Uniform snow	36	63,500	63	37	6.0	14,400 ± 1,700	0.23 ± 0.03	8 ± 1	47 ± 4	2.6 ± 0.2	90 ± 20
	Blade, rear ballast	Uniform snow	36	70,100	57	43	6.7	16,400 ± 2,300	0.23 ± 0.03	8 ± 1	51 ± 4	2.8 ± 0.2	90 ± 20
3/25	Blade, rear ballast	Packed trail, only broke traction once	36	70,100	57	43	6.7	14,500 ± 600	0.21 ± 0.01				340 ± 3
3/25	Blade, rear ballast (towing sleds)	Towed sleds uphill without breaking traction	36	70,100	57	43	6.7	25,400 ± 500	0.36 ± 0.01				370 ± 260
		Broke traction in soft snow with side slope						20,100 ± 200	0.29 ± 0.01				70
		Broke traction in soft snow with side slope						22,100 ± 400	0.32 ± 0.01				
		Broke traction in soft snow						21,400 ± 500	0.31 ± 0.01				

Table 1. Case drawbar tests conducted in March 2009. Last four values on 3/25 resulted from towing sleds past B1A. Self-propelled rut depth, power, and fuel consumption were from runs adjacent to drawbar tests.

Figure 10. Case Quadtrac, in its lightest configuration, towing the Caterpillar 931 during drawbar tests. The 931 had difficulty bringing the Case to a halt even with its tracks locked and bucket buried.

The baseline test on the Case, in the same configuration as used during GrIT08, produced unreliable results owing to failure of the load pin. Fortunately, we had two additional load pins and checked their calibrations against one another before continuing the tests. We also changed locations after the tests on 20 March to test in more uniform snow conditions.

All formal drawbar tests using the 931 as load vehicle produced fairly consistent but low results compared with the drawbar loads achieved without breaking traction during GrIT08 (21,000 ± 2000 lb or $DBP/W = 0.33 \pm 0.03$). We expected higher *DBP* by switching to 36-in.-wide tracks. The highest drawbar coefficient (20 March, 0.28 ± 0.05) was obtained on rough snow and had large variability between pulls. Some results are consistent with expectations: adding weight increased *DBP* provided the front and rear weight distribution was close to the target 55/45. Also, higher ground pressure or poor weight distribution produced deeper self-propelled ruts and higher power and fuel consumption.

The Case achieved its best drawbar performance while towing sleds past B1A on 25 March. It was in its heaviest configuration, with blade and ballast weights, but had lower ground pressure and better weight distribution than during GrIT08. Corrected for slope, the Case achieved a 4-s sequence of $DBP = 25{,}400 \pm 500$ ($DBP/W = 0.36 \pm 0.01$) without breaking traction while pulling the sleds uphill on strong snow ($E60 = 370 \pm 260$ J). More importantly, it developed high *DBP* (20,000–22,000 lb) prior to breaking traction at three locations while towing the sleds across soft snow between B1A and B2. Each of the measurements is the average of four 1-s duration peaks. In effect, these were operational drawbar tests. The snow strength, *E*60 = 70 J, was the same as the average from Camp Century to Summit obtained during GrIT08 (*E*60 = 70 ± 20 J).

We do not understand why the formal drawbar tests produced low results, but the sled-towing results suggest that the Case with 36-in. tracks, blade and ballast weights should achieve *DBP* = 21,000 ± 1000 lb across most of the GrIT route. Furthermore, with lower average ground pressure and better weight distribution, it should consume less self-propulsion power than during GrIT08.

5.2 Tucker Towing Performance

During GrIT08, the crew was understandably reluctant to push the Tucker to its towing limits for fear of breaking it. The March 2009 program allowed such tests in safer circumstances. Formal drawbar and endurance-towing tests were conducted to assess whether the Tucker could reliably tow more of GrIT's supplies and to quantify the towing performance of a low (1.8 psi) ground pressure vehicle.

The Case served as the load vehicle for Tucker drawbar tests, driving backwards at approximately 3 mph while connected to the Tucker. The Case then throttled back and the Tucker broke traction smoothly. In the uniform-snow test area (*E*60 = 90 ± 20 J) the Tucker achieved *DBP* = 8000 ± 400 lb or *DBP*/*W* = 0.55 ± 0.02 as the average of five–six pulls in each direction. This high drawbar coefficient is consistent with the Tucker's low ground pressure.

The Tucker also towed a 3000-gal. bladder sled on three separate 7-mile, 40-minute round trips towards B1 to assess its endurance under heavy loads. During two round trips on 24March, the Tucker developed average towing forces of *T* = 3900–4300 lb (about half its *DBP*) while averaging 8.0–8.5 mph, 0.9–1.0 gal./mile and producing ruts of 3 in. It was power-limited under these conditions, but an on-board mechanic (L. Lavine) judged that the engine and transmission temperatures were stable and within working ranges and that the tractor showed no obvious signs of strain. It is likely that, even on softer snow, the Tucker will be able to tow reliably about 20,000 lb of cargo on a flexible sled across most of the GrIT route at speeds exceeding 5 mph.

5.3 Bladder Sled Resistance

The GrIT08 bladders and cargo sleds used 1/2-in.-thick HMW-PE sheets as the sliding surface. Because they performed worse than expected, we decided to test welded UHMW-PE sheets as a substitute. This material was obtained with a silicone additive that the manufacturer claims lowers friction on materials such as stone and coal. To lessen the risk of weld failure, we specified 3/8-in.-thick sheets that measured 8 ft wide × 20 ft long and required only one transverse weld to form the sled. The thinner sheets also develop lower bending stresses over irregular terrain. Nevertheless, we specified two 1500-gal. bladders for the sled, reasoning that if the transverse weld did break, we could bolt the two sheets as a field repair. Figure 11 shows the resulting UHMW sled.

Figure 11. Bladder sled consisting of two welded sheets of UHMW-PE and two 1500-gal. bladders.

Budget and storage requirements limited the available fuel to 3000 gal. for the bladder sleds. Consequently, we tested the UHMW-PE bladder sled first and then transferred the fuel and bladders to an HMW-PE sled used during GrIT08 to test as a baseline. This sequence allowed us to tow the new UHMW sled several times, to assess its durability, before measuring towing resistance on the UHMW and HMW bladder sleds during back-back round trips with the Tucker on 24March. The round trips made it unnecessary to correct for slope effects on average towing resistance. No problems occurred with the UHMW weld during any of these tests.

The back to back round trips produced the following results: UHMW sled $T = 4300$ lb or $T/W = 0.20$; HMW sled $T = 3900$ lb or $T/W = 0.18$. That is, the UHMW sled performed slightly worse than the HMW sleds and both performed much worse than the HMW bladder sleds during GrIT08 (average $T/W = 0.13$). Even the weak snow from NEEM–Summit produced $T/W = 0.16$ for the HMW sleds.

Snow surface conditions and temperatures could play large roles. An identical round trip with Tucker towing the UHMW bladder sled on 21 March produced $T/W = 0.13$. This was before strong winds on 22 and 23 March that deposited 1–2 in. of fresh snow along the round-trip route. Although the air temperatures were similar on 21 March and 24 March (about –22°C) they were lower than most days during GrIT08. Results from Antarctica show that low air temperatures produce high startup resistance of HMW bladder sleds before the sleds warm up to develop lower resistance values. It is also possible that the flatter cross-section of the 3000-gal. bladders compared with the 1500-gal. bladders produces more uniform ground pressure and consequently lower resistance. Nevertheless, there appears to be no resistance benefit for UHMW sleds compared with HMW sleds and the latter avoid troublesome welds to join sheets into a sled.

5.4 Revised Spreader Bar

GrIT08 used triangular-plan spreader bars supported on small skis that derive from SPoT (Fig. 2 and 6). These function reasonably well but produced deeper ruts along the GrIT route than along the SPoT route owing to softer snow. Also, the attached sled tow plates could gouge snow and accumulate it.

Figure 12. New spreader bar consisting of square-section steel tubing wrapped with a sheet of HMW-PE to form a curved nose and to support bladder- and cargo-sled tow plates.

During March 2009, the GrIT team tested a simpler spreader bar designed to produce less sinkage and hence less towing resistance. Figure 12 shows the spreader bar attached to two cargo sleds. Towing is through cables connected to a beam of 10-in. × 10-in. × 33-ft-long square-section steel tubing. A sheet of HMW-PE wraps around the beam to form a ski nose and to provide a sliding surface for the bladder- or cargo-sled tow plates.

We did not separately measure the towing resistance of the GrIT08 spreaders or this new spreader. The new spreader did tow well with little sinkage or snow plowing. The cables provide operational flexibility and the beam slides well enough to be moved manually small distances to align tow plates and shackles for sled hook-up. One shortcoming is that the small end plates intended as lateral guides bent easily and need to be stronger.

6 Comparison with SPoT 08-09 Mobility

Most of the SPoT route consists of snow stronger than that along the GrIT route. Nevertheless, we include here key mobility results from SPoT 08-09 to set GrIT in context with its Antarctic counterpart.

A Case Quadtrac tractor (530 hp, 69,000 lb, 30-in.-wide tracks, 7.9 psi) achieved $DBP = 29{,}000 \pm 3000$ or $DBP/W = 0.42 \pm 0.04$ during tests near McMurdo. Two of these tractors were each usually able to tow twelve 3000-gal. fuel bladders on HMW-PE sleds across the Ross Ice Shelf (RIS). Although the tractors could achieve this performance over natural snow, the packed trail from previous seasons permitted 12-bladder towing to continue through a soft-snow “swamp” on the Ross Ice Shelf. The steady-state resistance of the bladder sleds towed behind the Case across the RIS was an impressively low $T/W = 0.061 \pm 0.004$ or $T = 1400 \pm 100$ lb per bladder.

An AGCO MT865 tractor (535 hp, 54,000 lb, 36-in.-wide tracks, 6.3 psi) achieved $DBP = 25{,}000 \pm 2000$ or $DBP/W = 0.47 \pm 0.03$ during tests near McMurdo. Compared with the Case, its lower ground pressure partially compensates for its lower weight to achieve high DBP. However, this two-track tractor more easily risked immobilization from steering corrections when pulling at high load. It also had more difficulty remaining stable on side slopes than the Quadtrac. Nevertheless, the MT865 easily pulled a fuel tank plus eight bladders across portions of the RIS and on occasion pulled 12 bladders.

The SPoT bladder and cargo sleds consisted of identical HMW-PE sheets as those for GrIT08 except that they were 68 ft long to carry two 3000-gal. fuel bladders in-line on the same sled. Some difficulties did arise with these sleds. Cracks developed in several HMW-PE sheets, causing sled failures. Many of these occurred at gouges formed during handling and assembly at McMurdo. Also, unrolling the HMW sheets at low temperatures (below 0°C) produced tub-shaped sleds that probably increased the risk of cracking. GrIT08 HMW-PE sheets and a similar sled tested at CRREL were all unrolled at air temperatures less than 20°C and developed no cracks during use.

The HMW bladder sleds also displayed high startup resistance at air temperatures below about –20°C on both the RIS and polar plateau. On each occasion, resistance decreased over periods of 20–50 minutes to much lower steady-state values. Figure 13 shows an example measured for the Case towing eight fuel bladders on HMW sleds across a region of soft snow called the "plateau swamp." This behavior is likely related to the energy needed to warm up the sled to develop a lubricating water layer at the sled/snow interface (Colbeck 1992). These peaks, coupled with heavier than planned cargo weights, resulted in daily shuttling of sled trains through the 160-mile polar swamp to South Pole.

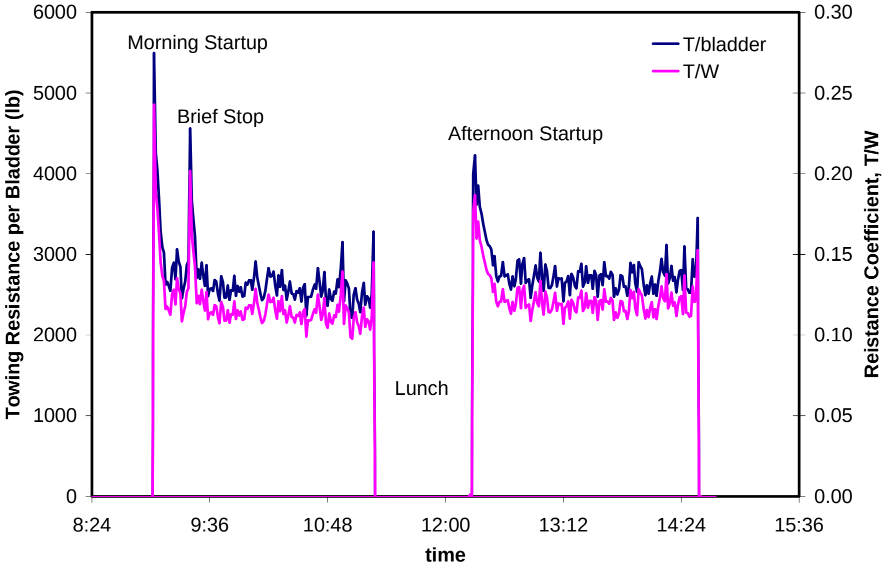

Figure 13. One-minute average towing resistance ($T = R + 3\sigma$) per bladder and resistance coefficient measured for Case Quadtrac towing eight-bladder sleds through SPoT "plateau swamp" on 12 December 2009. The Case developed 1-minute average *DBP* = 26,000 lb to overcome the morning startup peak and produced steady drawbar power of 190 hp during steady-state towing.

The plateau swamp had the weakest snow along the SPoT route, $E60 = 150 \pm 10$ J. Winter snow accumulation covered the trail with about 2 ft of natural snow, so the trail from previous years offered little mobility benefit. Nevertheless, the Case developed 1-minute average $DBP = 26{,}300 \pm 600$ lb ($DBP/W = 0.38 \pm 0.01$) to overcome startup peaks on three separate days along the polar swamp. Steady-state bladder–sled resistance through the swamp averaged $T/W = 0.11 \pm 0.01$ or $T = 2500 \pm 200$ lb per bladder towed behind the Case, and the Case was able to develop 190 hp of drawbar power while steadily towing eight bladders.

Over the plateau swamp, the MT865 tractor developed 1-minute average $DBP = 20{,}000 \pm 1000$ lb ($DBP/W = 0.37 \pm 0.02$) to overcome startup peaks. Generally speaking, it could tow slightly less than the Case. Interestingly, steady-state resistance of the bladder sleds towed behind the MT865 averaged $T/W = 0.09 \pm 0.01$ or $T = 2100 \pm 200$ lb per bladder. These values are slightly lower than for bladders towed behind the Case, perhaps because the MT865 produced shallower ruts or because it often drove along undisturbed (and therefore stronger) natural snow rather than in the ruts of leading tractors.

In the plateau swamp, a brief self-propulsion test showed that the Case produced 11 ± 1-in. ruts over natural snow while the MT865 produced 5 ± 1-in. ruts through the same area. The forward weight bias of the Case (10.3 psi) might account for its considerably deeper ruts.

SPoT uses a steel cargo sled to carry its spare parts and lubricants. This 35,000-lb sled has a tare weight of 25,000 lb and uses four steel skis. Over the plateau swamp, this sled towed very poorly: $T/W = 0.49$ or $T = 17{,}000$ lb to move only 10,000 lb of cargo. These figures are similar to those estimated for the GrIT08 fuel-tank sled and highlight the inefficiency of steel sleds compared with HMW sleds for fuel or cargo.

Measured DBP and steady-state resistance values suggest that the SPoT Case Quadtracs could tow 10 bladders through the plateau swamp at 5 mph. However, we have recommended that eight bladders be the upper limit in 2009–10 to avoid shuttling owing to startup resistance peaks. Similarly, we have recommended that the MT865 tractors tow a maximum of seven bladders through this area. Meanwhile, we have recommended trial of black HMW-PE sleds and black secondary envelopes to enclose the bladders, to increase solar warming of the sleds to reduce startup peaks (Colbeck and Perovich 2004). Also, we've recommended outfitting at least one Case with 36-in.-wide tracks to reduce ground pressure (6.6 psi) and thereby increase DPB and reduce self-propulsion losses. We have also recommended that all SPoT HMW-PE sheets be shipped in large-diameter coils and be unrolled and allowed to relax at room temperature before sled assembly. These recommendations will likely be adopted for SPoT 09-10.

7 GrIT Fleet Recommendations and Expected Performance

As with the initial feasibility assessment (Lever and Weale 2007), we must assume performance capabilities for the GrIT tractors and sleds to estimate deliverable cargo and fuel consumption for traverse scenarios of interest. We may now base these estimates on GrIT performance data with some expectations for improvements guided by SPoT experience.

7.1 Tractor Recommendations

Low ground pressure can yield high drawbar coefficients and low self-propulsion losses for tractors over snow. High tractor weight produces high DPB for a given ground pressure. Clearly, low ground pressure and high tractor weight are competing design requirements and are thus a rare combination in commercial tractors.

While at NEEM, the GrIT08 crew coordinated a demonstration test of NEEM's Pisten-Bully 300 (PB300) towing the four GrIT fuel bladders. This 460-hp tractor weighed about 22,000 lb. Its two wide tracks produce nominal ground pressure of about 1.2 psi (higher if porosity of tracks is included). The Case was able to tow the four bladders into NEEM at T = 13,500 lb and 6 mph (drawbar power 170 hp). The PB300 also towed these bladders through the same area at 6 mph. We may assume that the towing forces were the same for both tractors. This results in an impressive $DBP/W = 0.61 \pm 0.06$ for the PB300, attesting to the benefits of low ground pressure on drawbar efficiency in snow. However, the operator/mechanic noted that the PB300 was power limited, had high slip (approximately 20%), and had trouble executing even wide turns. Importantly, the operator expressed concerns about the PB300's reliability while towing that hard all day. The PB300 produced deep ruts (10 ± 2 in.) and threw snow high behind its tracks (Fig. 14), which undoubtedly produced high self-propulsion losses. Because the Case produced the same drawbar pull and power without reliability concerns, and is similar in cost to the PB300, it represents a better choice as the GrIT towing tractor.

Figure 14. Pisten-Bully 300 towing four GrIT08 bladder sleds at NEEM. Despite an impressive *DBP/W* = 0.61, the tractor was power-limited at 6 mph and its operator expressed reliability concerns about towing all day under these conditions.

Reliability requirements direct the choice of GrIT tractors towards agricultural tractors, with engines, drive trains, and chassis designed to operate efficiently at high power and drawbar forces day after day. Towards this end, we tested a John Deere 8530 tractor equipped with Soucy tracks on temperate snow in February 2009 (Lever 2009, Fig. 15). This 38,000-lb, rear-drive, front-assist tractor had an average ground pressure of 5.9 psi. It developed *DBP/W* = 0.38–0.40 over natural, groomed, and pack-trail snow conditions. Unfortunately, it is not clear how the tractor would perform over GrIT snow conditions without detailed mobility modeling or field trials. Its 40/60 rear-weight bias would increase during hard towing and could reduce its drawbar pull and available power. Also, because of its lower weight, two JD8530s are probably needed to replace the towing capacity of one Quadtrac. Because the JD8530 with Soucy tracks is more than half the cost of a Quadtrac and two operators would be needed, this change would incur higher capital and operating costs.

The AGCO MT865 is another candidate tractor (Fig. 16). As noted, it performed nearly as well as the Case on SPoT 08-09, including across the plateau swamp. Its track system is easier to clean than the Quadtrac's, which reduces daily maintenance effort. However, a well-balanced Case with 36-in.-wide tracks has very similar ground pressure, its extra weight provides a *DBP* advantage, and it has superior steering and side-slope performance compared to the MT865. Because these tractors are similar in cost, the MT865 does not possess a clear advantage over the Case for GrIT. As with SPoT, GrIT could acquire one of each of these tractors for head-head comparisons over several seasons, but the need for two sets of spare parts militates against this option.

Figure 15. John Deere 8530 tractor equipped with Soucy tracks prior to over-snow traction tests in Drummondville, Quebec, in February 2009.

Figure 16. AGCO MT865 tractor with crane connected to a fuel tank and eight fuel bladders on HMW sleds for towing across a portion of the Ross Ice Shelf during SPoT 08-09.

In GrIT08 form, the Case Quadtrac produced usable *DBP* = 21,000 ± 2000 lb (*DBP*/*W* = 0.33 ± 0.03) in the traction-limited region up to

NEEM. This exceeded our predictions based on de-rated Antarctic performance. During 2009 mobility tests, the Case achieved DBP = 21,000 ± 1000 lb in snow similar in strength to that from NEEM to Summit. In this form, the Case was heavier but with better weight distribution and its wider tracks produced lower average ground pressure (6.7 versus 7.2 psi). We therefore expect the Case to develop about 21,000 lb of *DBP* for the majority of the GrIT route. Also, with wider tracks and better weight distribution, the Case should produce shallower ruts and require less self-propulsion power than in GrIT08 form. It should thus be able to sustain 5 mph across the weaker snow from NEEM to Summit.

We know of no towing tractor that is clearly superior to the Case Quadtrac for use on GrIT. The effort needed to verify the superiority of an alternative towing tractor (or self-propelled cargo carried) would be substantial: preferably field trials over a significant fraction of the GrIT route or high-fidelity mobility modeling using detailed snow-strength parameters collected specifically for this purpose. Absent this effort, we recommend use of Case Quadtracs as the primary towing tractors for GrIT. The tractors should be similar to the heavy configuration Case tested in 2009: approximately 70,000 lb with 36-in. tracks and an approximate 55/45 weight distribution. Quadtracs are available in 530-hp engines at the same weight, and GrIT would benefit from the extra power during power-limited conditions from NEEM to Summit.

7.2 Sled Recommendations

The HMW-PE bladder and cargo sleds performed worse that predicted during GrIT08 and worse than similar sleds used during SPoT 08-09 through its plateau swamp. Reducing the resistance of these sleds is critical to higher mobility of the GrIT fleet. Recall that the GrIT08 bladder sleds averaged T/W = 0.13 (T = 2900 lb per bladder) but that the combined bladder and cargo sleds averaged T/W = 0.16 (T = 3600 lb per bladder) for the last 350 miles to Summit. We recommend several simple changes likely to improve the performance of these sleds.

Sled friction in cold conditions will decrease as sleds warm up and develop a lubricating water film at the snow interface (Colbeck 1992). Because the low-ground pressure sleds cause little snow compaction, friction is probably the dominate resistance term. The performance of the SPoT sleds across the plateau swamp (Fig. 13) supports this assertion. Interestingly, the GrIT08 and March 2009 data did not reveal a decrease in sled resistance from startup to steady state. It is possible that the sleds did not warm up sufficiently to produce a lubricating water film.

We recommend purchasing black HMW-PE sheets to increase solar warming of the sleds. This effect could be significant even during cloudy days (diffuse solar) and when sunlight can only reach the interface via scattering through the snow (Colbeck and Perovich 2004). We also recommend obtaining ½-in.-thick × 8-ft-wide × 68-in.-long HMW-PE sheets to carry two 3000-gal. bladders per sled. As suggested by SPoT 08-09 results, the longer sled will improve warming of the snow–sled interface, owing to longer contact time, compared with the single-bladder GrIT08 sleds. Half-inch sheet thickness is better than 3/8 in. for holding heat at the snow interface. To minimize risk of cracking, we recommend that the longer HMW sheets also be unrolled and allowed to relax at air temperature higher than 20°C.

SPoT plans to purchase secondary-containment envelopes to enclose its fuel bladders. We recommend that GrIT use these same envelopes. The envelope material should be dark, preferably black, to increase solar warming of the bladder and hence the underlying sled.

Compaction of weaker snow could play a role in increasing the resistance of GrIT bladder sleds compared with those of SPoT. While ruts made by bladder sleds are barely detectable for either traverse, the inboard bladders do round the ruts produced by the towing tractors, and the tractor ruts are generally deeper for GrIT owing to softer snow. To minimize this resistance, we recommend connecting HMW sleds, with two bladders inline, only to the outboard shackles on a spreader, which would thus straddle the tractor ruts most of the time.

It is likely that GrIT can achieve similar sled performance as SPoT, assuming that snow compaction plays a minor role in sled resistance. That is, $T/W = 0.11$ or $T = 2500$ lb per bladder are realistic estimates with these simple changes. That is, the Case with $DBP = 21{,}000$ lb should be able to tow eight fuel bladders or the equivalent cargo on HMW sleds across most of the GrIT route. Note that positive feedback is likely to occur if sled resistance is reduced, even incrementally. Lower towing resistance allows higher towing speeds which increases frictional heating of the sleds which lowers resistance even further. We recommend continued towing-resistance and tractor power monitoring to assess whether these changes succeed.

The towing resistance estimated for a full fuel-tank sled during GrIT08 was about 9500 lb near the transition and about 17,000 lb on the soft snow past NEEM. The higher tare weight (12,500 lb) and ground pressure (2.1 psi) contribute to this high resistance compared with bladder sleds. Also, heat conduction by the steel skis reduces the heat available to produce a lubricating water layer at the snow interface. For the same towing effort, the Case could tow four–seven bladders (3000 gal. each) on HMW sleds. Tanks sleds also cost about four times more than bladder sleds. GrIT cannot afford to pay these capital and efficiency penalties. We, therefore, recommend that GrIT only use bladder sleds to transport fuel. This necessitates daily fueling of the fleet from bladders. We consequently recommend that GrIT obtain an efficient and convenient system to permit daily fueling from bladders. SPoT obtained a high-capacity fuel pump that connected easily to a tractor's auxiliary hydraulic lines. This could be installed on the back of a tractor for convenient use.

GrIT might need to tow heavy cargo for delivery to NEEM or Summit. As with tank sleds, the high tare weight, ground pressure, and cost of steel sleds make them extremely inefficient for towing cargo. We recommend that heavy cargo only be towed on HMW or other flexible sleds. Minor improvements to the HMW cargo sleds used during GrIT08 should include fabric or net side skirts, to help contain the cargo, and rear spreader bars, to separate adjacent sleds. Anticipating future cargo needs, we recommend developing a flexible sled with a compliant interface to a lightweight, stiff deck. The stiff deck would provide a more conventional platform to secure cargo, while the interface would provide compliance over rough snow and distribute pressure evenly to the flexible sleds. Preliminary concepts suggest this sled would be much lighter, have lower ground pressure, and be less expensive than a steel cargo sled. To minimize development risk, we recommend full-scale testing at CRREL before field deployment. This development effort could be cost-shared with SPoT as they also need a lightweight cargo sled.

7.3 Operational Recommendations

Over flat snow, the Case should be able to tow eight bladders on HMW sleds. However, the numerous uphill slopes along the 60-mile transition zone reduce the tractor's drawbar pull and increase sled towing resistance. Essentially, the reliable towing capacity in this region is half that over level snow. We recommend that GrIT plan for intentional shuttling through the transition. This will eliminate stressful, ad-hoc shuttling based on random immobilizations with little, if any, increase in transit time. To allow for this, each spreader should carry only four 3000-gal. bladders, two in-line on each of two HMW sleds. These two sleds should be attached to the outside shackles of the new spreader bar to straddle the tractor ruts. The schedule could allow each tractor to shuttle half its sleds forward 15–20 miles, then return and shuttle the second half forward. The radar vehicle could spend the second half of the day surveying the route ahead for crevasses before returning to meet the tractors at camp. The fleet would thus plan to use 3–4 days to cross the transition zone without the uncertainty and stress of random immobilizations.

8 GrIT Economic Feasibility

8.1 Overview

Our original feasibility assessment (Lever and Weale 2007) considered scenarios to re-supply Summit Station via traverse to accrue benefits from reduced LC130 costs, fuel consumption, and air emissions. Prepared prior to GrIT08, we established targets for annual re-supply needs, estimated performance and cost parameters based on SPoT experience, and compiled LC130 costs and fuel consumption per flight offset to Summit. We also estimated traverse and LC130 air emissions using the method outlined by NSF/OPP in its comprehensive environmental evaluation of heavy traverse operations in Antarctica (NSF 2004). The analysis predicted significant cost, fuel, and emission reductions for all scenarios considered (two–four tractor single swings and a two-tractor dual swing).

As noted, results from GrIT08 revealed that feasibility estimates for tractor performance were reasonable but that the sleds experienced higher resistance than predicted. In addition, costs to operate the traverse were much higher than predicted. However, GrIT08 revealed some helpful developments: the fleet could fuel daily from a bladder, eliminating the need to tow a steel tank, crew accommodations could be much lighter than SPoT-based module sleds, and deliveries to NEEM en-route to Summit were beneficial to NSF/OPP. Importantly, GrIT08 verified that a safe route was possible from Thule to Summit, eliminating that uncertainty.

We prepared a revised feasibility assessment (Lever et al. 2008) that incorporated several changes: higher traverse operating costs, revised LC130 costs, the Tucker towing all fleet-support needs (except fuel), and annual GrIT deliveries to NEEM or other equivalent science camp while en-route to Summit. That assessment also examined the sensitivity of GrIT economic payback to improved sled performance and increased LC130 costs. The key scenario, the long-term economic feasibility of single traverse swings to re-supply NEEM and Summit, showed that a two-Case, one-Tucker fleet would break even at $6800/hr SAAM rate (the expected 2009 rate charged by the Air National Guard for LC130 flight time) if each Case could tow ten 3000-gal. fuel bladders. The same scenario would break even with eight bladders per Case if the SAAM rate increased by 20% to $8200/hr.

We use the 2008 feasibility assessment as the basis for the current analysis and present it here in more detail. It addresses the key question: is the traverse a tool to reduce the long-term logistics costs for NSF/OPP activities in Greenland?

8.2 Status Quo

The estimated annual logistics needs at Summit Station are 40,000 gal. of fuel, 200,000 lb of non-science cargo, and 120,000 lb of retro-cargo (Lever and Weale 2007). We assume here that NEEM or a similarly positioned science camp will require 15,000 gal. of fuel and 40,000 lb of cargo annually (Haggerty 2010).

LC130 ski-equipped aircraft flown by the Air National Guard (ANG) currently meet these needs via flights from Kangerlussuaq (abbreviated here as Kanger). Table 2 summarizes the performance data for the LC130 flights to NEEM and Summit.

Table 2. LC130 parameters for flights from Kanger to NEEM and Summit. The ANG uses 6.65 lb/gal. as fuel density.

Destination	Round-trip flight hours	Round trip fuel consumption (lb)	Payload delivered (lb)	Fuel consumed/payload delivered
NEEM	5.2	29,300	18,500	1.58
Summit	4.0	23,300	22,000	1.06

The negotiated 2009 SAAM rate charged by the ANG is $6816/hr of flying time. This includes fuel cost and a 10% discount for early scheduling of the flights. Additionally, the ANG charges to position aircraft in Greenland from its base at Scotia, NY. Over the last few years, these charges have averaged 75% of in-Greenland flight-hour costs (Haggerty 2010). We include these positioning costs and a 5% contingency on LC130 costs to cover aborts, multiple take-off slides, and cost to service flights and board crews in Kanger.

Note that this analysis assumes that the SAAM rate captures all LC130 costs to “rent” the aircraft, and we have made no provision to re-capitalize them. In fact, major overhauls of the LC130 are required periodically, and NSF/OPP contributes to these costs. These capital costs are not included here but would increase the cost to continue LC130 operations.

8.3 Traverse Scenarios

We focus here on a three-vehicle GrIT fleet: two Case Quadtracs to tow all fuel and deliverable cargo, and one Tucker SnoCat to tow accommodations, food, and fleet spare parts. This is a likely fleet configuration for GrIT in 2010 and can serve as a baseline to evaluate other options. The analysis here will vary the number of 3000-gal. fuel bladders (or equivalently 20,000 lb of cargo) on HMW sleds to seek the break-even performance requirement for this fleet. Table 3 shows mobility results to date for HMW bladder and cargo sleds to place these variations in context.

Table 3. Summary of measured bladder and cargo sled performance and equivalent number of 3000-gal. bladders (or 20,000-lb cargo units) towed behind a Case Quadtrac (*DBP* = 21,000 lb)

Circumstances	*T/W*	Resistance per bladder (lb)	Number of bladders per case
SPoT 08-09 Ross Ice Shelf (steady state)	0.061	1400	15
SPoT 08-09 plateau swamp (steady state)	0.11	2500	8.4
GrIT08 Thule to mile 355, just past NEEM	0.13	2900	7.2
GrIT08 mile 355 to Summit	0.16	3600	5.8
Mar 09 mobility tests	0.18	3900	5.4

The March 2009 tests on the Tucker showed that it could develop towing forces of 4100 ± 2000 lb at 8 mph without signs of strain. This force is adequate to tow 26,000 lb of gross weight at $T/W = 0.16$, the average performance of the HMW sleds from NEEM to Summit. That is, the Tucker should be able to tow at 8 mph a 6000-lb hard-shell galley/berthing module on well-designed skis plus 20,000 lb of supplies on an HMW sled. At lower speeds, the Tucker will develop forces approaching its measured $DBP = 8000 \pm 400$ lb, which should enable it to tow these same sleds up the slopes though the transition with few immobilizations. Thus, the Tucker would make a good fleet-support vehicle as well as a platform for GPR surveys.

Table 4 shows the estimated capital and operating costs for the traverse. The number of bladder sleds and spreaders varies with the assumed mobility performance, as does fuel consumption, so the table provides example costs for eight bladders per Case. Traverse fuel costs are based on

$4.20/gal., the cost of fuel in Thule as of November 2008. Notice that operating costs are about double the annualized capital costs.

Table 4. Estimated capital and operating costs for the traverse. Annualized capital costs assume a discount rate of 3% p.a. Traverse fuel costs are based on $4.20/gal.

Capital costs	Unit cost (including contingency)	Life	Number	Total annualized cost
Case Quadtrac, wide tracks & spares	$480,000	10	2	$112,541
Tucker SnoCat	$228,000	10	1	$26,729
Bladder, envelope, sled + tow plates	$30,000	5	varies with mobility	
New spreader	$18,000	10	varies with mobility	
Thule facility upgrade	$120,000	20	1	$8,066
Misc (e.g., radios, GPS, tents, etc)	$30,000	5	1	$6,551
Total capital cost, e.g.,8 bladders per Case				*$267,137*

Sled mobility affects whether the GrIT fleet has sufficient capacity to warrant a delivery to Summit or should just re-supply NEEM. A fleet of two Cases and one Tucker will consume about 14,100 gal. of fuel for a round trip of Thule to Summit, based on GrIT08 fuel consumption with 10% contingency added. This is essentially five bladders including reserve. The NEEM delivery requirements amount to the equivalent of seven bladders (five bladders and two cargo sleds, approximately 140,000 lb total). That is, the outbound fleet must have a towing capacity exceeding 12 bladders, or six bladders per Case, to warrant proceeding from NEEM to Summit. Otherwise, it should deliver all its cargo to NEEM and return to Thule.

Table 5 summarizes the delivery capabilities of the GrIT fleet based on sled mobility expressed as the number of bladders per Case tractor outbound from Thule. Deliveries to Summit are warranted for mobility of eight bladders per Case and greater, and the table separately accounts for the number of LC130 flights offset at each location. All scenarios show large fuel savings for traverse re-supply compared with LC130 re-supply. These fuel savings translate into proportional savings in carbon-dioxide emissions (about 22 lb-CO_2 per gallon of diesel fuel).

Table 5. Performance summary for GrIT fleet of two Case Quadtracs and one Tucker SnoCat. At a mobility level of six bladders per Case, the fleet has insufficient capacity warrant driving to Summit but slightly exceeds the delivery needs at NEEM. At higher mobility levels, the fleet can make deliveries to NEEM and Summit.

Bladders per Case	Delivered to NEEM (lb)	Delivered to Summit (lb)	Total Delivered (lb)	LC130 Offset NEEM	LC130 Offset Summit	LC130 Offset Total	LC130 Fuel (gal.)	Traverse Fuel (gal.)	Traverse Consumed/Delivered	Fuel Savings (%LC130)	Emissions (%LC130)
4	116,000	-	116,000	6.3	0.0	6.3	28,000	5,800	0.33	21	0.27
6	196,000	-	196,000	10.6	0.0	10.6	47,000	5,800	0.20	12	0.16
8	140,000	83,000	222,000	7.5	3.8	11.3	46,000	14,100	0.42	30	0.39
10	140,000	163,000	302,000	7.5	7.4	14.9	59,000	14,100	0.31	24	0.31
12	140,000	242,000	382,000	7.5	11.0	18.6	72,000	14,100	0.25	20	0.26

Lever and Weale (2007) argued that the SPoT and GrIT fleets, and their operational scenarios, are sufficiently similar that the air-emissions reductions estimated for the Antarctic traverse (NSF 2004) could be used to estimate the emission reductions in Greenland. Following this approach, Table 5 includes the average air emissions for traverse re-supply as a percentage of those for LC130 re-supply for each scenario. The emissions for traverse operations are all less than 0.4% of LC130 operations to deliver the same payloads. Although using average emission reductions neglects differences in impacts for the five pollutants (sulfur oxides, nitrogen oxides, carbon monoxide, exhaust hydrocarbons, and particulates), the traverse emissions are two orders of magnitude below those of LC130 for all pollutants.

Table 6 presents the annualized costs for GrIT for each mobility scenario. Only the bladder-sled, spreader, and fuel costs vary with scenario, but the other costs are included to show relative contributions. Annualize capital costs are roughly half of annual operating costs for all scenarios. Note that all costs except fuel include 20% contingencies on best-estimates for GrIT based on 2008 and 2009 experience.

Table 6. Annualized costs for GrIT based on mobility level.

Bladders per case	Tractors	Sleds + spreaders	Thule upgrade + misc.	Total capital	Operating	Fuel	Total annualized traverse
4	$139,270	$56,625	$14,617	$210,512	$528,000	$24,499	$763,010
6	$139,270	$82,828	$14,617	$236,714	$528,000	$24,499	$789,213
8	$139,270	$113,251	$14,617	$267,137	$528,000	$59,233	$854,370
10	$139,270	$139,453	$14,617	$293,340	$528,000	$59,233	$880,573
12	$139,270	$169,876	$14,617	$323,763	$528,000	$59,233	$910,995

Table 7. Annual LC130 costs and annual savings (loss) for GrIT based on mobility level. Net savings in orange are approximate break-even conditions for deliveries to NEEM only; net savings in green approximate break-even conditions for deliveries to NEEM and Summit.

	SAAM Rate $6,800/hr		SAAM Rate $7,500/hr		SAAM Rate $8,200/hr	
Bladders per case	LC130 cost	Annual savings (loss)	LC130 cost	Annual savings (loss)	LC130 cost	Annual savings (loss)
4	$401,000	$(362,000)	$441,000	$(322,000)	$485,000	$(278,000)
6	$676,000	$(113,000)	$743,000	$(46,000)	$818,000	$ 28,000
8	$666,000	$(188,000)	$733,000	$(121,000)	$806,000	$(48,000)
10	$844,000	$(36,000)	$929,000	$48,000	$1,022,000	$141,000
12	$1,022,000	$111,000	$1,125,000	$214,000	$1,237,000	$326,000

Table 7 presents the economic bottom line: estimated annual cost savings or losses for GrIT based on mobility performance for three different SAAM rates. Given uncertainties in these estimates, we take ± $50,000 net annual savings or loss as break-even conditions.

At the 2009 SAAM rate ($6800/hr), each Case tractor would need to be able to tow 10 fuel bladders outbound from Thule for GrIT to break even. This requires bladder-sled performance of $T/W = 0.095$, substantially better than current performance except along SPoT's Ross Ice Shelf (Table 3). Planned shuttling through the transition (i.e., five bladders per Case) would still be feasible. Also, after delivering seven bladders to NEEM and consuming just over one bladder of fuel, the Cases would only need to tow six bladders each from NEEM to Summit. This demands sled performance of only $T/W = 0.16$, the average value along that route segment achieved during GrIT08. The critical route segment is thus from B11D to NEEM. This is actually the route segment where GrIT08 experienced its best mobility, with the Case able to tow all sleds on several occasions. Nevertheless, we recommend that improved sled performance be demonstrated before GrIT heads out with 10 bladders per Case.

Increasing the SAAM rate by 10% (to $7500/hr) does not appreciably change break-even conditions for deliveries to Summit; 10 bladders per Case would still be needed. However, GrIT would break even by resupplying NEEM entirely by traverse, with mobility of only six bladders per Case needed. GrIT08 has already demonstrated this level of performance ($T/W = 0.16$).

With an additional 10% increase in SAAM rate to $8200/hr, GrIT would break even with mobility performance of eight bladders per Case. This corresponds to $T/W = 0.11$, the performance possible through SPoT's plateau swamp and probably within reach for GrIT with the simple changes recommended (black sleds and envelopes, two bladders in-line per HMW sled, sleds attached on outside shackles of spreaders). Again, the high mobility demand is from B11D to NEEM. Most of the route would demand much lower mobility: planned shuttling of four bladders per Case along the transition; travel with only four bladders per Case ($T/W = 0.23$) from NEEM to Summit. If SAAM rates are likely to increase, and GrIT systematically seeks to improve sled mobility, this scenario is very attractive.

Note that these scenarios do not require that the Cases with wide tracks perform better than the Case with narrow tracks did during GrIT08. We expect that the new tractors will achieve at least *DBP* = 21,000 lb and that self-propulsion losses will be lower, so that higher average speeds should be possible. Modestly improved sled mobility is all that's needed for GrIT to break even economically under these scenarios.

We have previously noted (Lever et al. 2007; 2008) that our economic analysis probably understates the program-wide benefits of GrIT. Other benefits that could be significant include:

- Cost savings possible by shipping cargo to Thule rather than flying it to Kanger.
- Cost savings possible by pre-fabricating buildings and towing them to Summit rather than building them at Summit from components.
- The scientific value of significantly reduced air emissions realizable by traversing cargo to Summit rather than flying it there.
- The value of the traverse to establish and remove large science camps elsewhere in Greenland compared with building skiways and flying in and out all camp infrastructure.
- Operational cost savings at Kanger for a large numbers of LC130 flights offset.
- The traverse as a hedge against unrestrained LC130 costs (SAAM rate and major aircraft overhauls).

9 Conclusions

GrIT has established a safe route to re-supply NEEM and Summit Station via overland traverse. The measured drawbar performance of the Case Quadratc tractor is similar to that expected based on 20% de-rating of Antarctic performance for this tractor. However, the bladder sleds used during GrIT08 and variants tested during March 2009 perform significantly worse than their SPoT counterparts under steady-state conditions. The latter do display high startup resistance that decreases to lower steady state values over 20–50 minute periods. This behavior probably reflects a warm-up period needed to develop a lubricating liquid-water layer at the sled–snow interface.

Feasibility analysis reveals that a GrIT fleet consisting of two Case tractors and a Tucker fleet-support vehicle would recover its capital investment and operating costs at current LC130 SAAM rates by re-supplying NEEM and partially re-supplying Summit provided the Case tractors could tow ten 3000-gal. bladders each outbound run from Thule. If the SAAM rate increases by 20%, to $8200/hr, the same GrIT fleet would break even on costs by towing eight bladders per Case. This mobility level is likely, provided GrIT systematically seeks to improve bladder-sled performance.

The critical route segment is from just past the transition (B11D) to NEEM, a distance of about 230 miles. Planned shuttling along the 60-mile transition will reduce immobilizations from steep slopes, and GrIT08 demonstrated the mobility needed to tow four–six bladders per Case across 410 miles to Summit after re-supplying NEEM.

10 Recommendations

- Acquire two Case Quadtrac tractors with 36-in.-wide tracks as its primary towing vehicles. We know of no other vehicles with superior demonstrated performance over polar snow fields for comparable costs.
- Acquire a Tucker SnoCat as its fleet-support vehicle and GPR platform. The Tucker will perform well in both capacities, serving to verify a safe route through the transition and towing accommodations and all supplies (except fuel) for the fleet.
- Implement, in partnership with SPoT, a systematic program to improve the performance of fuel-bladder sleds. In the near term, this should include lab tests and field trials of black HMW-PE sleds, black bladder-containment envelopes, and in-line towing of two 3000-gal. bladders on the same sled. Field monitoring of towing forces, sled temperatures, and tractor performance should be an integral part of this effort.
- Tow fuel only in bladders on flexible sleds and acquire the pumping system needed for efficient daily fueling from bladders. This will eliminate the need to tow an inefficient and expensive tank sled for daily fueling.
- Develop, in partnership with SPoT, a lightweight cargo sled that interfaces a stiff deck with a flexible HMW sled. Tare weight should be less than 5000 lb for a 20,000-lb cargo capacity, with ground pressure close to 1 psi. This sled would present a more conventional arrangement for securing cargo while retaining low towing resistance of simple HMW cargo sleds.
- Plan to shuttle half-loads up the 60-mile transition onto the main ice sheet. This would eliminate frustrating and time-consuming random immobilizations and add little if any time to cross the transition. A convenient arrangement would be four bladders per spreader with two bladders in-line on HMW sheets attached to the ends of the spreader. This would permit easy connections for four or eight bladders per Case and allow the sleds to straddle the tractor ruts to minimize snow-compaction losses along those ruts.
- Develop, in partnership with SPoT, the snow-properties database and analysis tools needed accurately to model and predict sled and tractor performance. Positive feedback for incremental sled or tractor im-

provements, through increased travel speeds and sled warming, will amplify performance improvements. By coupling a good predictive model with an economic assessment, it will be possible to pursue development ideas most likely to provide payback for GrIT.

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14. ABSTRACT

The mobility and economic feasibility of resupplying Summit Camp on the Greenland ice cap from Thule AFB via a 1410-mile (round trip) overland traverse was examined following safe and successful implementation of the Greenland Inland Traverse (GrIT) proof-of-concept in 2008. The mobility and economic assessments focused on delivery capabilities for a tractor fleet consisting of two prime movers and one fleet-support vehicle and its economics compared with re-supply by LC130 aircraft. The mobility feasibility was based on tractor drawbar and sled resistance measurements collected during the GrIT08 proof-of-concept. Sled resistance measurements indicate GrIT will recover its capital investment and operating costs with a mobility performance of eight 3000-gal. fuel bladders towed per prime mover given a 20% increase in LC130 hourly costs. This mobility level is likely, provided GrIT systematically improves bladder-sled performance (currently six bladders per prime mover) through incremental improvements like the use of black fuel bladders and black HMW-PE sleds. As argued in our previous work, an overland traverse represents an economic buffer against unconstrained and likely LC130 SAAM hourly rate increases. It is recommended that GrIT acquire two prime movers with 36-in. wide tracks (70,000 lb each with a drawbar pull of 21,000 lb) and a lighter-weight fleet-support vehicle with 4100 lb of drawbar pull. Loads should be shuttled up the 60-mile transition onto the main ice sheet to eliminate frustrating and time-consuming immobilizations caused by weak snow and steep grades. Additional improvements, such as the development of a lightweight cargo sled, a snow-properties database, and fleet performance analysis tools should be developed in partnership with the South Pole Traverse (SPoT).

15. SUBJECT TERMS

	HMW-PE sled resistance	NEEM
Fuel-bladder sleds	HMW-PE sleds	Oversnow mobility
Greenland Traverse (GrIT)	LC130 economics	Oversnow traverse economic feasibility

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15. SUBJECT TERMS (cont'd)

South Pole Traverse (SPoT)

Thule Air Base, Summit Station

Tractor drawbar