ERDC/CRREL SR-16-2

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Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Economic Analysis of the Greenland Inland Traverse (GrIT)

James H. Lever, Geoff Phillips, and Jay Burnside

June 2016

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Abstract

The Greenland Inland Traverse (GrIT) transports fuel and cargo over snow to resupply science stations on the Greenland ice sheet from Thule Air Base. GrIT offers an alternative to the traditional LC-130 airlift resupply from Kangerlussuaq, Greenland. In this report, we assess the economics of GrIT relative to airlift resupply operations by comparing the costs of each mode to deliver the same fuel and cargo based on data from the 2012 and 2014 seasons.

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Preface

This study was conducted for National Science Foundation, Division of Polar Programs (NSF-PLR), Arctic Research Support and Logistics (RSL), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ARC-14-12, "Support for GrIT." The technical monitors were Renee Crain, RSL Associate Program Manager, and Patrick Haggerty, RSL Program Manager, NSF-PLR.

The work was performed Dr. James H. Lever (Force Projection and Sustainment Branch, Dr. Sarah Kopczynski, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), and Geoff Phillips and Jay Burnside, CH2M Hill Polar Services, Polar Field Services (CPS-PFS). At the time of publication, Jason Weale was the program manager for EPOLAR. Dr. Loren Wehmeyer was Chief of the Research and Engineering Division of ERDC-CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

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

Acronyms

ACL	Allowable Cabin Load
ARCS	Air-Ride Cargo Sled(s)
AW	Airlift Wing
AWO	Atmospheric Watch Observatory
B/C	Benefit/Cost
CPS	CH2M Hill Polar Services
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
DOD	Department of Defense
EPOLAR	Engineering for Polar Operations, Logistics, and Research
ERDC	Engineer Research and Development Center
GLT	Greenland Telescope
GPR	Ground-Penetrating Radar
GrIT	Greenland Inland Traverse
HMW-PE	High Molecular Weight Polyethylene
MOA	Memorandum of Agreement
NEEM	North Greenland Eemian Ice Drilling
NSF	National Science Foundation
NYANG	New York Air National Guard
PFS	Polar Field Services
PLR	Division of Polar Programs
R&D	Research and Development
RSL	Research Support and Logistics

SAAM	Special Assignment Airlift Mission
SAGE	Sunlight Absorption on the Greenland Ice Sheet Experiment
SCAT	Strategic Crevasse Avoidance Team
SPoT	South Pole Traverse
USAP	U.S. Antarctic Program

Unit Conversion Factors

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

Executive Summary

The Greenland Inland Traverse (GrIT) transports fuel and cargo over snow to resupply science stations on the Greenland ice sheet from Thule Air Base. Operated on behalf of the National Science Foundation (NSF), GrIT offers an alternative to the traditional LC-130 airlift resupply from Kangerlussuaq, Greenland. In this report, we assess the economics of GrIT relative to airlift resupply operations by comparing the costs of each mode to deliver the same fuel and cargo based on data from the 2012 and 2014 seasons. We also sought to identify and quantify, insofar as possible, the component costs of the GrIT and airlift resupply modes to link each mode's unique characteristics with its attendant costs.

We compiled costs in two broad categories: operating and capital. Operating costs are incurred annually to support airlift or GrIT activities. Capital costs are expenses incurred in one year that continue to provide benefits for several years (e.g., equipment purchases). Capital costs can be converted to equivalent annualized costs to smooth the economic impact across their useful lives. Alternatively, they can be considered sunk costs and thus ignored. We include here parallel cost calculations: ones that include annualized capital costs and ones that omit capital costs. As much as possible, we followed standard techniques in engineering economics (Grant et al. 1982) to compare the two modes on an equivalent annual-cost basis.

GrIT's deliveries and costs are straightforward to compile because GrIT operates as a stand-alone activity. Costs include tractors and sleds, operational fuel and labor, and resources to verify a safe route through the heavily crevassed initial 60 miles of its route. We also include the research and operational support provided by personnel at the Cold Regions Research and Engineering Laboratory (CRREL).

Table E1 summarizes the GrIT12 and GrIT14 fleet compositions and payloads delivered. In the cost analyses, we explicitly account for GrIT12's significant fuel deliveries to North Greenland Eemian Ice Drilling (NEEM). For simplicity, we treat the small GrIT14 fuel deliveries to NEEM and fuel staged for the Sunlight Absorption on the Greenland Ice Sheet Experiment (SAGE) as if they were delivered to Summit.

Table E1. GrIT 2012 and 2014 deliveries.

		NEEM and SAGE Deliveries		Summit Deliveries		Total Deliveries
Traverse	Tractor Fleet	Fuel (lb)	Cargo (lb)	Fuel (lb)	Cargo (lb)	Fuel + Cargo (lb)
GrIT12	Two Case Quadtrac 485s, Case Magnum 335, Tucker SnoCat	63,500	-	114,900	103,300	281,700
GrIT14	Three Case Quadtrac 485s, Case Quadtrac 500, Tucker SnoCat	17,700	-	138,300	245,800	401,800

Airlift costs are more diffuse, with airlift support spread across NSF's Arctic Research Support and Logistics (RSL) program. Important airlift costs include the Special Assignment Airlift Mission (SAAM) rate (cost per flying hour), the cost to position the aircraft in Greenland, the cost to stage cargo to Greenland, the cost to operate Raven as an alternate landing site, Summit skiway construction and maintenance costs, and cargo-handling costs. The average LC-130 payload delivered to Summit is 21,100 lb, and round-trip flying time is 4.0 hr. The corresponding values for NEEM are 18,500 lb and 5.2 hr. These values allow us to convert GrIT deliveries to the equivalent LC-130 flights and costs needed to deliver the same payloads.

Table E2 compares the cost per pound of payload delivered to Summit for the scenarios analyzed. Note that airlift costs are higher for cargo than for fuel because airlifted cargo must first be staged to Kangerlussuaq whereas fuel is purchased directly at Kangerlussuaq. We have used the cost per pound for C17 cargo staging from Stewart Air Base, Newburgh, NY, as the most economical mode. GrIT stages its cargo to Thule via no-charge sealift from Norfolk, VA, and purchases fuel directly at Thule. That is, GrIT pays no staging costs for either payload, and its delivery cost per pound is thus the same for fuel and cargo.

On a cost-per-pound basis for Summit deliveries, GrIT12 was more expensive than airlift for fuel delivery but less expensive for cargo. Relative to airlift, the larger GrIT14 season achieved similar cost per pound for fuel delivery and significantly less cost per pound for cargo delivery. Excluding capital costs decreases delivery costs per pound for both modes by about 20%.

Table E2. Cost per pound for Summit fuel and cargo deliveries by GrIT12 and GrIT14 compared with the corresponding airlift costs per pound.

Analysis	GrIT (cost per lb delivered)		Airlift (cost per lb delivered)	
	2012	2014	2012	2014
Capital Included				
Fuel	$5.5	$5.8	$4.4	$5.8
Cargo	$5.5	$5.8	$6.2	$7.8
Capital Excluded				
Fuel	$4.3	$4.5	$3.4	$4.7
Cargo	$4.3	$4.5	$5.2	$6.7

Table E3 summarizes the 2012 and 2014 total delivery costs for GrIT, accounting for the specific mix of fuel and cargo deliveries made. The table also shows the corresponding airlift costs that would have been incurred to deliver the same payloads. The net annual economic benefits from GrIT are the differences between airlift and GrIT total costs for each season, and the corresponding benefit/cost (B/C) ratios are the ratios of airlift to GrIT costs. These calculations follow the standard approach to compare a new investment with the status quo (Grant et al. 1982): offset airlift costs are treated as benefits to GrIT's operation. As noted, the analysis for 2012 explicitly accounts for the GrIT12 deliveries to NEEM. Whether capital costs are included or excluded, GrIT12 essentially broke even while the larger GrIT14 saved about $500,000. The calculated B/C ratios for GrIT increase when we exclude capital costs for both modes.

Table E3. 2012 and 2014 total delivery costs, net annual economic benefit, and benefit/cost ratio for GrIT compared with airlift.

Analysis	GrIT Cost to Deliver Payload		Airlift Cost to Deliver Payload		GrIT Net Annual Benefit (Cost)		GrIT Benefit/Cost	
	2012	2014	2012	2014	2012	2014	2012	2014
Capital Included	$1,563,000	$2,347,000	$1,554,000	$2,825,000	$(9,000)	$478,000	0.99	1.20
Capital Excluded	$1,202,000	$1,826,000	$1,237,000	$2,402,000	$36,000	$576,000	1.03	1.32
LC-130 Capital Excluded	$1,563,000	$2,347,000	$1,314,000	$2,516,000	$(249,000)	$170,000	0.84	1.07

Table E3 also shows results from an analysis specifically requested by NSF-RSL: include GrIT capital costs but omit capital costs and upgrade and overhaul costs for the LC-130 fleet. This analysis reflects RSL's perspective that it will purchase new GrIT capital equipment (e.g., tractors) as needed but that it does not expect to contribute to LC-130 replacement or overhaul as the aircraft reach the end of their useful lives. From this perspective, GrIT12 lost money, but the larger GrIT14 saved RSL $170,000.

RSL also requested analysis of the cost per gallon of fuel at Summit, which is of special interest when considering investments in renewable energy technologies for the station. Component costs include the fuel purchase price, cost for delivery to Summit, and storage and transfer costs. On-site renewable energy production could offset these costs. Table E4 summarizes fuel costs at Summit for GrIT and airlift delivery modes.

Table E4. Fuel cost per gallon at Summit, averaged across 2012–14.

Analysis	2012–14 Average Price ($/gal.)	Average Delivery Cost ($/lb)	Average Delivery Cost ($/gal.)	Fuel Storage and Transfer ($/gal.)	Total Delivered Fuel Cost ($/gal.)
Capital Included					
Airlift	$4.4	$5.1	$35.5	$1.5	$41
GrIT	$3.7	$5.7	$39.9	$1.5	$45
Capital Excluded					
Airlift	$4.4	$4.0	$28.3	$0.2	$33
GrIT	$3.7	$4.4	$30.8	$0.2	$35

GrIT can achieve benefits over LC-130 airlift beyond cost-per-pound savings. The most important quantitative benefit derives from the capability of air-ride cargo sleds (ARCS) to deliver oversized cargo safely and smoothly. Near-term examples include the new Atmospheric Watch Observatory (AWO), large components of the Greenland Telescope, and prefabricated buildings for Isi Observatory and its support camp. Cost savings would include no-charge sealift staging to Thule versus C17 staging to Kangerlussuaq, and low-cost stateside or Thule assembly versus airlift of materials and high-cost Summit assembly. Moreover, GrIT enables the delivery of large, complex items that cannot feasibly be subdivided to satisfy the size or weight limits of an LC-130 (e.g., the Greenland Telescope main dish).

Other GrIT benefits not monetized include significant (99.9%) air-emissions reductions near Summit, science opportunities created along the safe

GrIT transit corridor, science depots or camps emplaced along the route or along off-shoot spurs, and a hedge against unexpected LC-130 cost increases (e.g., the SAAM rate or aircraft modernization).

GrIT is a relatively recent alternative to airlift resupply of Summit Station. We expect that GrIT's efficiency of operations will improve as the mode matures. For example, the newly developed ARCS are slightly less efficient than fuel-bladder sleds in terms of towing resistance per pound of payload. Through research cooperatively supported by the South Pole Traverse, we expect that the performance of ARCS will approach that of bladder sleds. This improvement would significantly improve GrIT's economic performance. Quantitatively, if GrIT14's ARCS had been able to carry 20% more payload for the same tractor effort, net benefits in 2014 would have increased by $330,000.

Our analyses show that GrIT as currently configured can provide a modest cost savings relative to LC-130 airlift. Likely efficiency gains, reduced emissions, and the ability to deliver critical, oversized cargo make GrIT extremely attractive as an ongoing resupply mode for Summit Station.

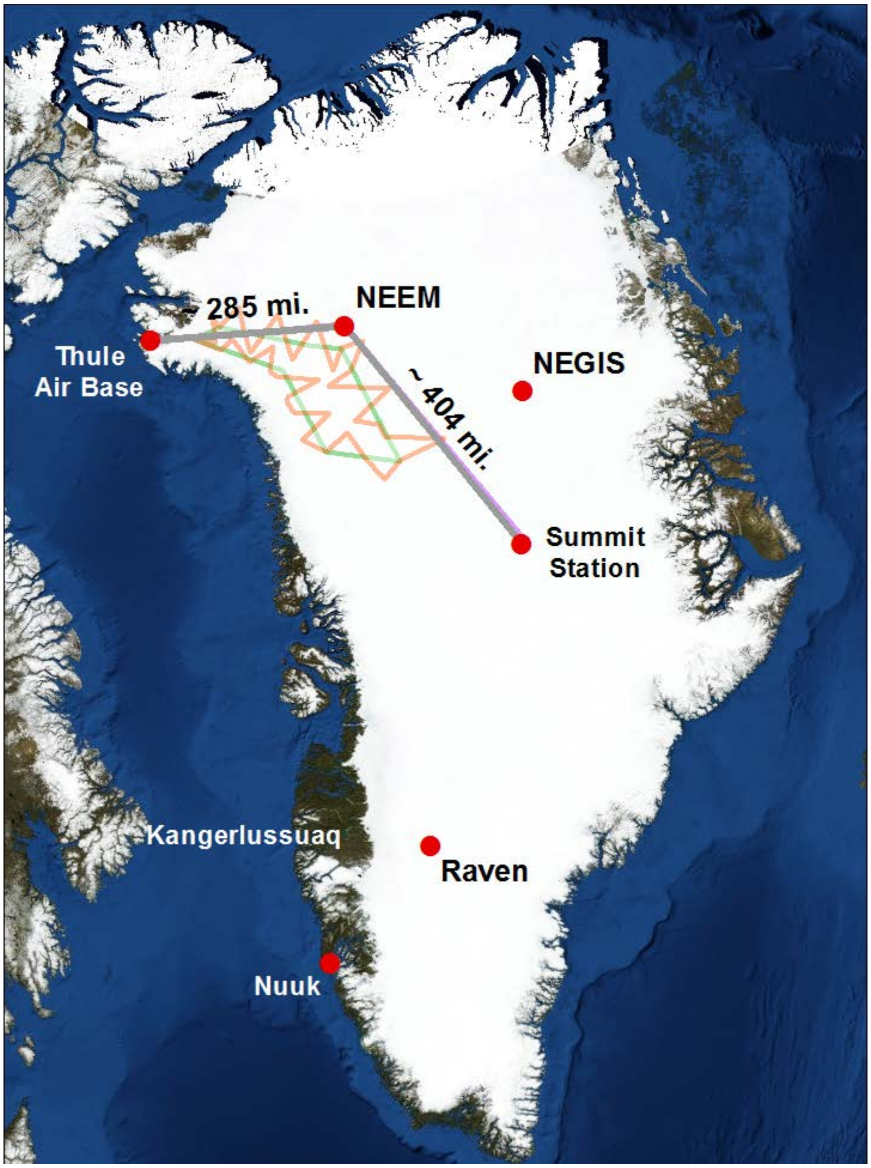
1 Introduction

1.1 Background

The Greenland Inland Traverse (GrIT) transports fuel and cargo over snow to resupply science stations on the Greenland ice sheet from Thule, Greenland (Figure 1). Operated on behalf of the National Science Foundation's Arctic Research Support and Logistics (NSF-RSL) program by its Arctic prime support contractor CH2M Hill Polar Services (CPS), GrIT offers an alternative to traditional airlift resupply from Kangerlussuaq (Kanger), Greenland. GrIT completed its inaugural season in 2008 and has conducted resupply operations in 2010, 2011, 2012, and 2014. Its fleet has ranged from one to four primary tractors towing sled trains consisting of evolving sled technology co-developed with NSF's U.S. Antarctic Program (USAP) and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Summit Station has annually been the main recipient of GrIT's fuel and cargo deliveries, with the Danish–U.S. North Greenland Eemian Ice Drilling (NEEM) site and the Sunlight Absorption on the Greenland Ice Sheet Experiment (SAGE), a deep-field science traverse, receiving smaller deliveries of fuel.

Initial feasibility assessments (Lever and Weale 2011a, 2011b) identified the preferred route, recommended initial tractor and sled equipment, and estimated fleet size, payloads, and tractor–sled mobility performance needed to break even economically relative to airlift resupply. Sled improvements adopted for GrIT10 showed that the target mobility performance was within reach, despite softer snow and smaller fleet sizes when compared with USAP's more mature South Pole Traverse (SPoT) operations (Lever 2011a).

Figure 1. The GrIT route from Thule to Summit by way of NEEM, approximately 740 miles one-way. GrIT's safe route and logistics infrastructure has enabled more deep-field science projects (e.g., 2014 SAGE snow surveys, shown south and west of NEEM). (Image from i-cubed 15 m eSAT, ESRI World Imagery, updated October 2011.)



1.2 Objectives

Our main objective was to assess the economic performance of GrIT relative to airlift resupply by comparing each mode's costs to deliver the same fuel and cargo. We based our analyses on GrIT's 2012 and 2014 seasons. These were the most ambitious GrIT operations to date and reflected the technological advancements that were made to optimize lightweight fuel and cargo sleds for GrIT's payload requirements and snow conditions. Importantly, by using actual costs and deliveries for 2012 and 2014, we sought to assess GrIT's economic performance more accurately than was possible for earlier analyses (Lever and Weale 2011a, 2011b).

A secondary objective was to identify and quantify, insofar as possible, the component costs of the GrIT and airlift resupply modes. In effect, we sought to link each mode's unique characteristics with its attendant costs.

In addition, we sought to establish cost and performance baselines against which variations in the GrIT and airlift resupply modes could be assessed. These baselines could then be used, for example, to assess the economic benefits from sled improvements relative to the costs to develop those improvements. Similarly, future analyses could assess the economic benefits resulting from procuring and transporting prefabricated buildings via GrIT rather than airlifting materials for on-site construction at Summit.

1.3 Approach

The analyses here generally follow a recently completed economic analysis of SPoT (Lever and Thur 2014) although the cost structures for LC-130 airlift to Greenland are quite different. Essentially, we documented the operation of each mode, used the achieved deliveries and actual costs for GrIT in 2012 and 2014 to calculate cost per pound of payload delivered, computed the corresponding flights needed and attendant costs required for airlift delivery of the same payload weight, and assessed the economic performance of GrIT relative to airlift by treating offset airlift costs as benefits to GrIT. As much as possible, we followed standard techniques in engineering economics (Grant et al. 1982) to compare the two modes on a common annual-cost basis.

Although comparisons based on cost per pound neglect potentially significant cost differences for oversized cargo (e.g., prefabricated buildings), the analyses can be expanded to assess those costs for specific cases as more information becomes available.

2 GrIT Route, Fleet Configuration, and Operational Schedule

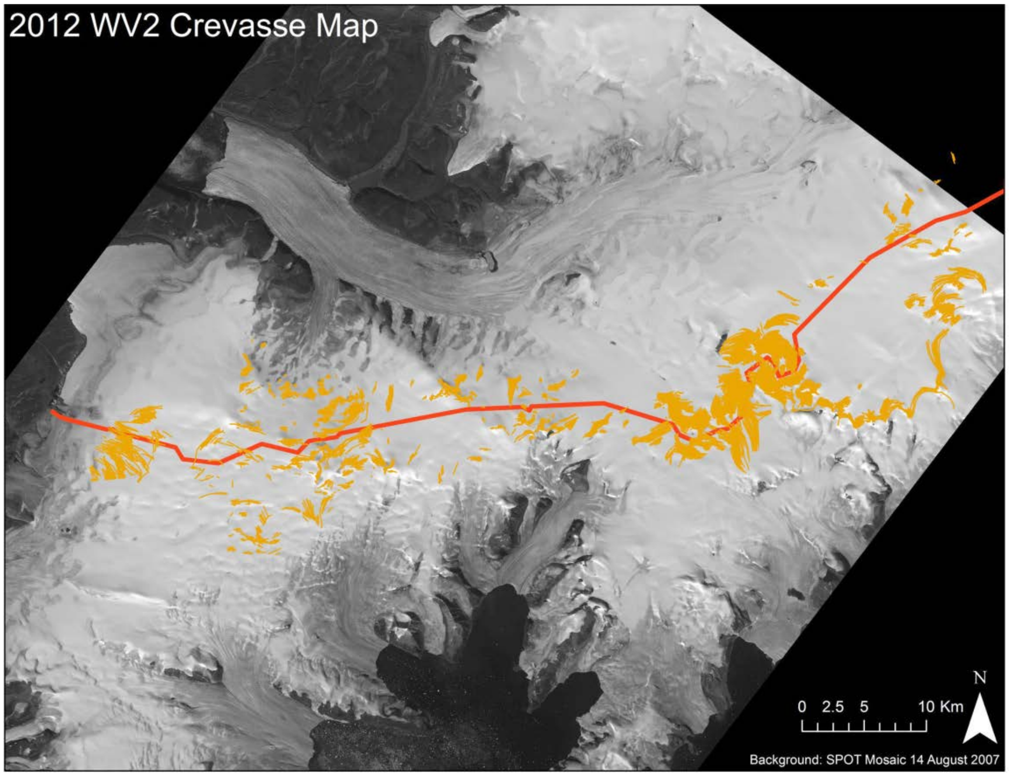
2.1 GrIT's Route and Its Operational Implications

GrIT stages its operations from Thule Air Base (Figure 1). Its route begins with 15 miles of gravel road to the ice edge and then climbs and weaves along approximately 60 miles of crevasse-ridden terrain before reaching the main Greenland ice sheet. The remaining 680 miles through NEEM to Summit are nearly flat, but the snow can be cold and soft, constraining the mobility of tractors and sleds. This route structure strongly influences GrIT's operations.

GrIT purchases its fuel (for consumption and delivery) directly in Thule and to date has benefitted from no-cost sealift of cargo, including heavy or oversized items, from Norfolk, VA. While some indoor fabrication of sleds does occur in Thule, all sleds and payloads must be transported over the road to the ice edge for final assembly and loading. GrIT pays Greenland contractors to transport its sleds and payloads around Thule and to the ice edge.

The 60-mile crevasse zone is dynamic on annual time scales. GrIT fields a Strategic Crevasse Avoidance Team (SCAT) to locate and validate a safe route each year. Prior to the season, CRREL requests and obtains from the Polar Geospatial Center visual-band satellite imagery that was acquired near the end of the summer melt season, typically in late August or early September. This imagery has 1 m resolution and can reveal crevasses along the route as dark, linear features. CRREL personnel manually outline these features on the imagery (Figure 2). SCAT's five-person crew then conducts ground-penetrating-radar (GPR) surveys during the following spring, using the marked imagery as a guide, to identify a safe path through the crevasse zone. SCAT conducts its initial surveys on day trips from Thule and then mounts a field campaign to survey the farther sections. SCAT typically requires about three weeks to validate a safe route, during which GrIT is staging and loading sleds at the ice edge.

Figure 2. Crevasse map developed by CRREL using summer 2011 WorldView-2 satellite imagery to delineate visible crevasses (*orange lines*) along the 2012 GrIT route (*red line*).



2.2 Fleet Configuration

Figure 3 shows some photographs of GrIT's tractors and sleds. GrIT has mainly used Case Quadtrac 485s as towing tractors. GrIT12 had two of these tractors, a smaller Case Magnum 335, and a Tucker SnoCat, the latter for light duty to tow the crew quarters. In 2014, GrIT used three Case Quadtrac 485s, one Case Quadtrac 500, and the Tucker SnoCat. This fleet provides GrIT with about half the towing capacity of one of SPoT's eight-tractor fleets. In both 2012 and 2014, SCAT used the Tucker SnoCat, the crew quarters, and a Pisten Bully 100 to conduct its route surveys.

Since 2010, GrIT has towed its fuel in lightweight, flexible bladder sleds. Jointly developed with SPoT and CRREL, these bladder sleds are far more efficient and less expensive than steel fuel sleds (Lever and Weale 2012). They consist of commercial 3000 gal. fuel bladders strapped to extruded sheets of half-inch thick high molecular weight polyethylene (HMW-PE). Across most of GrIT's route, a Quadtrac 485 can reliably tow a group of eight 3000 gal. bladders (two bladders inline on each of four sheets of HMW-PE). Extensive mobility data gathered during GrIT10 demonstrated that warmer bladder sleds tow easier than colder ones (Lever

2011a). For this reason, GrIT and SPoT switched from tan to black bladders in 2011–12 to capitalize on solar gain to warm the sleds, thereby reducing towing resistance.

Figure 3. *Upper*, GrIT Case Quadtrac 485 tractor in 2011 alongside fuel-bladder sleds staged at the ice edge. (Photo courtesy of Robin Daves.) *Middle*, Case Magnum 335 tractor towing loaded air-ride cargo sleds in 2012. *Lower*, beginning in 2012, GrIT has used black fuel bladders to increase solar gain and thereby warm the sleds to reduce towing resistance. The *orange* Tucker SnoCat and *red* crew quarters are in the middle of the image. (Photo courtesy of Robin Daves.)

Compared with South Pole Station, Summit Station requires a higher fraction of its annual delivered payload as rigid cargo rather than fuel. With CRREL's technical assistance, GrIT has led development of lightweight cargo sleds that seek to achieve the payload efficiency (i.e., payload weight per unit towing force) of bladder sleds. The resulting air-ride cargo sleds (ARCS) use air-filled pontoons as lightweight, compliant suspensions between HMW-PE sheets and wood-framed cargo decks. In 2012, GrIT deployed several tube-in-pouch ARCS, where the pontoons reside inside fabric pouches that connect between the decks and the HMW-PE sheets (Lever 2011b). Each ARCS deck measured 15 ft 8 in. wide × 20 ft long and was fabricated from engineered lumber. The tare weight was only 5000 lb for a design payload weight of 25,000 lb. Figure 4 shows the main group of four ARCS loaded for GrIT12's outbound trip. These ARCS provide a very smooth, stable ride over rough snow. GrIT14 used similar tube-in-pouch ARCS to transport its large cargo items (Figure 5). ARCS are still under development, but we are confident that they soon will achieve the payload efficiency and reliability of bladder sleds.

Figure 4. GrIT12 ARCS loaded for the outbound trip to Summit Station. The two front sleds carried two 24,000 lb empty steel fuel tanks. One rear sled carried a 14,000 lb roller-packer while the other rear sled carried food and tools inside a tent enclosure. As with its bladder sleds, GrIT towed the assembly of four adjacent HMW-PE sheets through a ski-nose spreader bar.

Figure 5. GrIT14 ARCS carried a prefabricated berthing module (*red*) along with two empty steel fuel tanks and food, tools, and miscellaneous payload inside tent enclosures.

2.3 Operational Schedule

GrIT typically begins its operational season in late January or early February, with initial work focused on tractor maintenance, sled preparation, and SCAT staging. SCAT attempts to complete its route survey in March, allowing GrIT to depart Thule in early April. GrIT must tandem tow its sled trains up the 3%–5% grades common through the crevasse zone. This dictates that the tractors shuttle loads forward and then return for a second load. Depending on temperatures and snow conditions, GrIT may also need to tandem tow (shuttle) the sled trains across sizable portions of the main ice sheet. Shuttling the sled trains slows the daily advance from 50 to 60 miles to half that distance, increasing the time needed to complete the outbound trip. GrIT stops for a couple of days to deliver fuel to NEEM and then proceeds to Summit for its main fuel and cargo deliveries. GrIT may also load some retro cargo at Summit to return to Thule (and thence to the United States). Note that GrIT tows the fuel it needs for tractor and camp operations in addition to its food, spare parts, and living accommodations. It remains entirely self-sufficient throughout its delivery operations.

GrIT must return all tractors and sleds to Thule by June 1 to avoid safety hazards from seasonal melt along the lower portion of the crevasse zone and demobilization problems resulting from snow loss at its staging area at the land–ice transition. This deadline imposes a strict schedule constraint on GrIT and pushes the onset of SCAT and GrIT operations into mid-winter when the temperatures are cold and sunlight hours are short.

3 Cost Model

We compile costs in two broad categories: operating costs and capital costs. Operating costs are incurred annually to support airlift or GrIT activities. Examples include crew labor and tractor fuel. Capital costs are expenses incurred in one year that continue to provide benefits for several years. Equipment purchases and one-time research costs are examples of capital costs.

Capital costs can be converted to equivalent annualized costs to smooth their apparent economic impact across their useful lives. This is common practice when comparing the economic performance of investments with differing sequences of outlays and receipts (Grant et al. 1982). For example, GrIT12 used two Quadtrac 485 tractors purchased for GrIT11 and one newly purchased Magnum 335. If we assume that the useful life of a tractor is 10 years, essentially we apply one-tenth of the purchase price of each tractor to the cost of conducting GrIT12 (with a small correction based on discount rate to account for the time-value of money). This allows us to add equivalent capital costs to annual operating costs to determine the equivalent total cost of GrIT12.

Alternatively, capital cost can be considered as sunk costs (i.e., past outlays) and ignored when considering two future investment scenarios. Examples might include NSF-owned LC-130 aircraft and GrIT tractors. Viewing capital costs as sunk costs makes sense if time horizons are short and the equipment will not need to be replaced (recapitalized) during that time. Rather than make that judgment for each capital asset, we include here parallel cost calculations: ones that include annualized capital costs and ones that omit all capital costs as sunk costs.

Regardless of the treatment of capital costs, we include annual costs to maintain capital assets. For example, the labor and parts needed annually to maintain GrIT's tractors are included in GrIT's operating costs separately from annualized capital costs.

4 GrIT12 and GrIT14 Deliveries and Costs

Table 1 summarizes GrIT's fleet compositions and deliveries made in 2012 and 2014. In 2012, GrIT used the Case Magnum 335 as a towing tractor on its outbound trip and then delivered it to Summit as payload (for annual use grooming the Summit skiway). GrIT12's delivered cargo thus includes the 37,300 lb Magnum tractor and the large steel fuel tanks and roller-packer shown in Figure 4. Note that we use a fuel density of 7.0 lb/gal. to convert gallons to pounds delivered.

Table 1. GrIT 2012 and 2014 tractor fleets and deliveries.

		NEEM and SAGE Deliveries		Summit Deliveries		Total Deliveries
Traverse	Tractor Fleet	Fuel (lb)	Cargo (lb)	Fuel (lb)	Cargo (lb)	Fuel + Cargo (lb)
GrIT12	Two Case Quadtrac 485s, Case Magnum 335, Tucker SnoCat	63,500	-	114,900	103,300	281,700
GrIT14	Three Case Quadtrac 485s, Case Quadtrac 500, Tucker SnoCat	17,700	-	138,300	245,800	401,800

In 2014, GrIT14 used four Case Quadtracs to tow its fuel and cargo sleds. None were delivered as payload. The increased towing capacity of GrIT14 relative to GrIT12 allowed it to deliver 42% more total payload. During both years, GrIT shuttled its sled trains for most outbound days, achieving only 28 miles/day in 2012 and 21 miles/day in 2014. Shuttling increased fuel consumption and crew days in the field, thereby increasing costs. GrIT14 also experienced several fabric failures on its ARCS and a tractor mechanical breakdown, which caused significant in-field downtime for repairs.

Table 2 itemizes GrIT's capital costs. We selected a 2% per annum discount rate to annualize capital costs across the useful life of each item. Note that GrIT12 delivered the Case Magnum 335 as payload to Summit, so its capital cost does not accrue to GrIT.

Table 2. Summary of GrIT capital costs for specific items.

Capital Costs	Unit Cost	Life	Annualized Unit Cost
Case 485 and spares	$550,000	10	$61,200
Magnum and spares	$0	10	$0
Tucker	$250,000	10	$27,800
Pisten Bully	$165,000	15	12,800
Crew quarters	$250,000	10	$27,800
Dual-bladder sled and tow plates (6000 gal.)	$30,000	5	$6,400
Spreader (parts and labor)	$10,000	10	$1,100
ARCS (parts and labor)	$30,000	5	$6,400
Weatherport coverings	$2,000	10	$200
Snowmobiles	$10,000	10	$1,100
Auger for crevasse mitigation	$5,400	20	$300
Misc. (e.g., radios, GPS, tools, etc.)	$200,000	5	$42,400
CRREL R&D to initiate GrIT, establish route, design sleds, etc.	$750,000	20	$45,900
Durabase	$31,958	5	$6,800
Road survey	$4,996	20	$300

Table 3 and Table 4 itemize GrIT12 and GrIT14 costs, respectively. Annualized capital costs are 21%–22% of total costs, and labor costs dominate operating costs. Both years include CRREL's research and development (R&D) costs to support GrIT. CRREL's annual costs to support SCAT, to assist with sled assembly, and to conduct mobility tests exceed the annualized capital costs for CRREL to help initiate GrIT (e.g., to assess GrIT's feasibility, to design and revise sleds, and to help establish procedures).

The cost for GrIT to conduct its annual survey to establish a safe route, via SCAT, are included within GrIT's capital and operating costs (Tables 3 and 4). Owing to the level of detail required, we did not separately compile SCAT costs as part of the present effort. Nevertheless, such an undertaking in the future could help reveal the cost-operational linkages for SCAT's critical role within GrIT.

Table 3. GrIT12 actual costs and cost per pound delivered.

Capital Costs	Number	Annualized Cost	Capital	No Capital Costs
Case 485 and spares	2	$122,500		
Magnum and spares	1	$0		
Tucker	1	$27,800		
Pisten Bully	1	12,800		
Crew quarters	1	$27,800		
Dual-bladder sled and tow plates (6000 gal.)	7	$44,600		
Spreader (parts and labor)	3	$3,300		
ARCS (parts and labor)	5	$31,800		
Weatherport coverings	2	$400		
Snowmobiles	2	$2,200		
Misc. (e.g., radios, GPS, tools, etc.)	1	$42,400		
CRREL R&D to initiate GrIT, establish route, design sleds, etc.	1	$45,9000		
Total Annualized Capital Costs			*$361,700*	*$0*
Operating Costs		**Annual Cost**		
Fuel		$81,000		
Operational—PM		$151,900		
Operational—labor		$421,900		
Trades labor		$121,200		
Vehicle maintenance		$28,300		
Subcontracts, communications, and intercompany		$65,400		
Materials		$34,300		
Travel		$137,600		
Food		$11,300		
Freight		$7,200		
Medical		$8,000		
Equipment rental		$12,100		
Permits and outreach		$3,300		
CRREL annual R&D (SCAT, sled revisions, and mobility tests)		$118,500		
Total Operating Costs			*$1,201,600*	*$1,201,600*
Total annual GrIT12 cost			$1,563,300	$1,201,600
GrIT12 cost/lb delivered			*$5.5*	*$4.3*

Table 4. GrIT14 actual costs and cost per pound delivered.

Capital Costs	Number	Annualized Cost	Capital	No Capital Costs
Case 485/500 and spares	4	$244,900		
Tucker	1	$27,800		
Pisten Bully	1	12,800		
Crew quarters	1	$27,800		
Dual-bladder sled and tow plates (6000 gal.)	8	$50,900		
Spreader	4	$4,500		
ARCS (parts and labor)	4	$25,600		
Weatherport coverings	2	$400		
Durabase	1	$6,800		
Snowmobiles	2	$2,200		
Auger for crevasse mitigation	1	$300		
Misc. (e.g., radios, GPS, tools, etc.)	1	$42,400		
CRREL R&D to initiate GrIT, establish route, design sleds, etc.	1	$45,900		
CRREL R&D to analyze and improve system efficiency	1	$28,600		
Total Annualized Capital Costs			*$520,900*	*$0*
Operating Costs		**Annual Cost**		
Fuel		$91,900		
ops-PM		$272,400		
ops-labor		$744,400		
Trades labor		$44,700		
Vehicle maintenance		$46,600		
Subcontracts, communications, and intercompany		$182,600		
Materials		$65,000		
Travel		$166,500		
Food		$11,100		
Freight		$6,500		
Medical		$0		
Equipment rental		$0		
Permits and outreach		$1,400		
CRREL annual R&D (SCAT, sled revisions, and mobility tests)		$192,700		
Total Operating Costs			*$1,825,700*	*$1,825,700*
Total Annual GrIT14 Cost			$2,346,600	$1,825,700
GrIT14 cost/lb delivered			*$5.8*	*$4.5*

5 Airlift Operations and Costs

The LC-130 fleet consists of four aircraft owned by NSF and six aircraft owned by the Department of Defense (DOD). Through a Memorandum of Agreement (MOA), the 109th Airlift Wing (109th AW) of the New York Air National Guard (NYANG) operates and maintains the fleet on behalf of NSF for Polar airlift missions (Antarctica and Greenland). During each Greenland flight period, the 109th AW stages LC-130s from its base in Scotia, NY, to Kangerlussuaq, Greenland; flies a series of resupply missions from Kanger to Summit, NEEM, and other sites in Greenland; and then flies the planes back to Scotia. The aircraft takeoff and land on wheels at Kanger, but they land and takeoff on specially designed skis at Summit and NEEM (Figure 6). The airfields at these locations, called skiways, consist of groomed and partially compacted snow.

The round-trip distance, altitude increase, and snow-strength of the skiway all combine to establish the allowable cabin load (ACL) for an LC-130 flight. Summit and NEEM thus spend significant effort to construct and maintain their skiways to maximize strength and hence ACL for each flight. Based on several years of data, round-trip flying times from Kanger are 4.0 hr to Summit and 5.2 hr to NEEM, and the corresponding average ACLs are 21,100 lb at Summit and 18,500 lb at NEEM.

Figure 6. Ski-equipped LC-130 at Summit Station during cargo transfer.

5.1 LC-130 capital costs

The LC-130 fleet represents a substantial capital investment for DOD and NSF, and some of its annualized capital cost could be apportioned to the Greenland airlift. While NSF is currently the major user of all 10 LC-130s, it is possible that DOD will replace its six aircraft when the need arises. Thus, we limit NSF's capital investment to that of four LC-130 aircraft.

As with previous replacements, we assume a wheeled C130 would be purchased and retrofitted with skis. A new C-130J is likely to cost approximately \$70M to \$80M depending on the number ordered (U.S. Air Force 2015, 35; National Defence and the Canadian Forces 2010). We assume the addition of skis would increase the replacement cost of an LC-130 to about \$90M per plane.

Estimating the useful life of the LC-130 is difficult. The 109th AW aircraft are 20- to 30-year-old LC-130H series, which replaced earlier LC-130Ds after 25 years of service (Colin 2012; NYANG 2012). The NSF-owned aircraft are older airframes, transferred from the Navy's VXE-6 squadron, but were upgraded to LC-130H in the early 2000s. It is possible that these aircraft could be maintained, overhauled, and upgraded indefinitely, but this seems unlikely. Rather, we use 50 years as the life for these assets and note that repair and upgrade costs will probably escalate from historical levels. We again use a 2% per annum discount rate.

Note that the LC-130 fleet also provides airlift support for USAP. The Arctic airlift averages about 370 flying hours per year, and that of USAP averages about 2500 hours per year. That is, the LC-130 fleet flies about 2900 hours per year on behalf of NSF-PLR. The annualized capital cost of the four NSF-owned LC-130s thus converts to \$3,990 per flying hour.

5.2 Airlift operating costs

5.2.1 SAAM rate

The NSF-RSL pays for the 109th AW to fly the LC-130s in Greenland through a charge called the Special Assignment Airlift Mission (SAAM) rate. The SAAM rate is charged per flying hour, and it includes crew, fuel, and routine-maintenance costs. RSL receives a 10% discount on the SAAM rate for pre-planned flights. Table 5 shows the discounted SAAM rates charged to RSL from 2006–15. The discounted SAAM rates were \$6,761 in 2012 and \$7,394 in 2014 and applied to all Summit and NEEM resupply flights flown during those years.

Table 5. Discounted SAAM rates, distribution of charged flying hours, and ratio of positioning hours to on-island hours for 2006–15.

Year	Discounted SAAM Rate ($/hr)	On-Island Flying Hours	Positioning Flying Hours	Total Flying Hours	Positioning/On-Island Ratio
2006	$4,065	173	89	262	52%
2007	$4,269	136	194	330	143%
2008	$6,116	293	243	536	83%
2009	$6,816	191	135	326	71%
2010	$6,270	181	172	352	95%
2011	$7,009	208	236	444	114%
2012	$6,761	204	211	415	104%
2013	$7,215	158	215	374	136%
2014	$7,394	96	159	255	166%
2015	$8,339	208	180	388	86%

5.2.2 Positioning costs

The 109th AW typically stages three LC-130s from Scotia to Kanger at the start of each flight period. These flights can be 6–7 hr depending on weather conditions and ACL, which mostly includes science cargo and passengers. Fortunately for RSL, the 109th AW normally charges for only one of the three aircraft, with the remaining aircraft paid through its training budget for flight crews to practice Polar takeoffs, landings, and other operations. Nevertheless, flight hours charged to RSL to position the LC-130s have averaged close to the flying hours charged for in-Greenland ("on-island") flying hours (Table 5). For 2012 and 2014, charged positioning flying hours were 104% and 166%, respectively, of the charged on-island flying hours. We therefore apply these ratios to the Summit and NEEM flying-hour SAAM costs to prorate positioning costs across delivery flights.

5.2.3 Raven operations

As part of its agreement with the 109th AW, NSF pays to construct and maintain a skiway on the ice sheet near Kanger, called Raven (Figure 1), to serve as an alternate landing site and an airfield to practice on-snow landings and takeoffs. RSL and USAP split the annual costs to operate Raven, $230,000 and $150,000, respectively. Here, we prorate RSL's cost to the Summit and NEEM resupply flights based on their shares of total on-island flying hours (204 hr in 2012 and 96 hr in 2014, Table 5).

5.2.4 Repairs, overhauls, and upgrades

As established by the MOA, NSF must pay to repair an LC-130 damaged during missions to support NSF (operational or training flights). In addition, NSF must pay to upgrade its own aircraft to satisfy new DOD requirements for LC-130s. These aircraft are currently 20–30 years old. At present, we do not have access to historical repair, overhaul, or upgrade costs. We include a modest value of $50,000 per year for each of the four NSF-owned LC-130s to serve as a placeholder and warning that these costs could increase substantially as the aircraft continue to age. We assume that RSL and USAP would split the repair, overhaul, and upgrade costs based on their respective share of total flying hours.

5.3 Skiway maintenance costs

Crew at Summit annually construct the skiway at the beginning of the season and maintain it during each flight period. They use the Case Magnum 335 to tow the roller-compactor delivered by GrIT12, a land plane, or a drag. CPS and CRREL have been optimizing and tracking skiway-maintenance effort at Summit. We include here the annualized capital costs of the Magnum and grooming equipment, fuel costs to operate the Magnum to construct and maintain the skiway, and related labor costs. We approximate the cost per gallon of fuel as an average of GrIT and airlift fuel-delivered costs. We include delivery costs for the grooming equipment but no delivery cost for the Magnum (it delivered itself on GrIT12). Also, we use an effective labor rate of $112/hr, which includes wages ($65/hr) and a food and lodgings day rate of $400 for a 60 hr workweek.

Table 6 summarizes annual skiway maintenance costs at Summit. We assume that similar costs apply to NEEM. Note that the fuel needed to maintain the skiway constitutes more than half of the annual cost.

Table 6. Summit skiway construction and maintenance costs.

Capital Costs	Unit Cost	Life (year)	Annualized Cost	Annualized Cost Excluding Capital
Magnum 335 (including spare parts)	$300,000	10	$33,400	$-
Land plane, drag, roller-packer	$187,100	15	$14,600	$-
Labor	**Rate ($/hr)**	**Annual Hours**		
Effective labor rate (Summit)	$112			
Season prep (Construction)		50	$5,600	$5,600
Maintenance during season		230	$25,700	$25,700
Equipment maintenance		40	$4,500	$4,500
Fuel Consumption	**Cost ($/gal)**	**Usage**		
Average cost/gal., capital included	$43			
Average cost/gal., capital excluded	$34			
Magnum Consumption (gal./ hr)		12		
Annual hours		280		
Annual fuel cost			$145,200	$113,700
Total Annual Skiway Cost			$228,800	$149,500
Skiway Cost per Summit Flight (20 flights)			$11,400	$7,500
Skiway Cost per NEEM Flight			$11,400	$7,500

5.4 Payload handling costs

GrIT pays all costs to stage and load its fuel and cargo in Thule and assists with offloading payloads at NEEM and Summit. We include here corresponding payload-handling costs for the airlift at Kanger, Summit, and NEEM. Table 7 summarizes these costs.

Table 7. Airlift payload handling costs for Kanger–Summit and Kanger–NEEM resupply flights.

Capital Costs	Cost	Life (year)	Annualized Cost	Cargo or Fuel Flights	Cost/Flight	Cost/Flight Excluding Capital
Summit loader	$130,400	10	$14,205	10	$1,400	$-
Kanger loader	$100,000	10	$11,133	14	$800	$-
Kanger K-loader	$130,000	10	$14,472	14	$1,100	$-
Kanger pickups (2 at $10,000 each)	$20,000	10	$2,227	14	$200	$-
Summit fuel pump	$7,100	10	$735	10	$100	$-
Labor	**Rate($/hr)**	**Hours/Flight**				
Kanger cargo handling	$112	20			$2,200	$2,233
Summit cargo handling	$112	20			$2,200	$2,233
Kanger fuel handling	$112	10			$1,100	$1,117
Summit fuel handling	$112	20			$2,200	$2,233
NEEM fuel handling	$112	20			$2,200	$2,233
Average Kanger–Summit Payload Handling					$5,700	$3,900
Average Kanger–NEEM Payload Handling					$5,700	$3,900

5.5 Greenland cargo staging

GrIT does not pay for sealift-based cargo staging from Norfolk, VA, to Thule Air Base because it is covered under NSF's support agreement with the Air Base. However, airlift cargo destined for Summit and NEEM must be flown to Kanger because the latter lacks a deep-water port. The 109th AW rarely flies cargo to Kanger on its positioning flights. The most economical method to stage major cargo (equipment, construction materials, etc.) is a C17 SAAM round-trip mission from Stewart Air Base operated by the NYANG 105th AW. Note that fuel delivered by airlift to Summit and NEEM is purchased directly in Kanger and thus does not incur a staging cost.

Table 8 summaries the costs to stage airlift cargo to Greenland. These costs include the C17 flight costs and costs to deploy CPS personnel to Stewart to prepare the cargo. Although the 105th offers 90,000 lb of ACL for the outbound C17 flight, payload volume normally limits the total weight to less than 80,000 lb.

Table 8. Airlift cargo-staging costs.

Parameters	Fixed Values	2012	2014
C17 ACL (lb)	80,000		
SAAM rate ($/hr)		$11,952	$13,071
Stewart–Kanger–Stewart flying hours	10		
Labor rate for cargo handling ($/hr)		$45	$46
Per diem for cargo handling ($/day)		$139	$143
Cargo prep person-days	51		
Hours per work day	8		
Costs per Flight			
Flying time Stewart–Kanger–Stewart		$119,500	$130,700
Cargo prep labor		$18,300	$18,900
Cargo prep hotel and per diem		$7,100	$7,800
Cargo prep car and airfare		$2,700	$2,800
Total prep cost		*$28,100*	*$29,500*
Total cost/flight		*$147,600*	*$160,200*
C17 Staging Cost/lb		$1.8	$2.0

5.6 Total airlift costs

Tables 9 and 10 summarize airlift costs for fuel and cargo delivered to Summit and NEEM in 2012 and 2014 for the cases of capital costs included and excluded, respectively. As noted, round-trip flying times from Kanger are 4.0 hr to Summit and 5.2 hr to NEEM, and the corresponding average ACLs are 21,100 lb at Summit and 18,500 lb at NEEM.

Table 9. Airlift costs, including capital costs, for 2012 deliveries to Summit and NEEM and 2014 deliveries to Summit.

Item	Comments	Annualized Cost	2012 Cost/hr	2014 Cost/hr	2012 Summit Flight	2012 NEEM Flight	2014 Summit Flight
LC-130 Capital Costs	NSF-owned aircraft	$2,864,100	$3,990	$3,990	$15,900	$20,700	$15,900
LC-130 Operating Costs							
SAAM rate	cost per on-island flying hr		$6,761	$7,394			
Positioning to/from Greenland	cost per on-island flying hr		$7,000	$12,300			
Raven Operations	cost per on-island flying hr		$1,100	$2,400			
Fuel	included in SAAM rate		$-	$-			
Planned Maintenance	included in SAAM rate		$-	$-			
Overhaul/ Upgrades	NSF-owned aircraft	$200,000	$70	$670			
Total Operating Costs			*$15,000*	*$22,100*	*$59,800*	*$77,800*	*$88,500*
Skiway Maintenance					$11,400	$11,400	$11,400
Payload Handling					$5,700	$5,700	$5,700
Total Cost per Flight					$92,900	$115,600	$121,600
Cargo Staging Cost/lb	C17 Stewart–Kanger				$1.8	$1.8	$2.0
Total Cost/lb Delivered							
Fuel					$4.4	$6.3	$5.8
Cargo					$6.2	$8.1	$7.8

Table 10. Airlift costs, excluding capital costs, for 2012 deliveries to Summit and NEEM and 2014 deliveries to Summit.

Item	Comments	Annualized Cost	2012 Cost/hr	2014 Cost/hr	2012 Summit Flight	2012 NEEM Flight	2014 Summit Flight
LC-130 Capital Costs	NSF-owned aircraft (4)	$-	$-	$-	$-	$-	$-
LC-130 Operating Costs							
SAAM rate	cost per on-island flying hr		$6,761	$7,394			
Positioning to/from Greenland	cost per on-island flying hr		$7,000	$12,300			
Raven Operations	cost per on-island flying hr		$1,100	$2,400			
Fuel	included in SAAM rate		$-	$-			
Planned Maintenance	included in SAAM rate		$-	$-			
Overhaul/Upgrades	NSF-owned aircraft (4)	$200,000	$70	$70			
Total Operating Costs			*$15,000*	*$22,100*	*$59,800*	*$77,800*	*$88,500*
Skiway Maintenance					$7,500	$7,500	$7,500
Payload Handling					$3,900	$3,400	$3,400
Total Cost per Flight					$71,200	$88,600	$99,400
Cargo Staging Cost/lb	C17 Stewart-Kanger				$1.8	$1.8	$2.0
Total Cost/lb Delivered							
Fuel					$3.4	$4.8	$4.7
Cargo					$5.2	$6.6	$6.7

6 Comparative Performance of GrIT and Airlift

6.1 Economic performance for 2012 and 2014

Table 11 summarizes the cost per pound for the actual payloads delivered to Summit by GrIT12 and GrIT14, with capital costs included and excluded. Note that airlift costs are higher for cargo than for fuel because airlifted cargo must first be staged to Kanger via C17 whereas fuel is purchased directly at Kanger. GrIT stages its cargo to Thule via no-charge sealift and purchases fuel directly at Thule. That is, GrIT pays no staging costs for either payload, and its delivery cost per pound is thus the same for fuel and cargo.

Table 11. Cost per pound for Summit fuel and cargo deliveries by GrIT12 and GrIT14 compared with the corresponding airlift costs per pound.

	GrIT (cost per lb delivered)		Airlift (cost per lb delivered)	
Analysis	2012	2014	2012	2014
Capital Included				
Fuel	$5.5	$5.8	$4.4	$5.8
Cargo	$5.5	$5.8	$6.2	$7.8
Capital Excluded				
Fuel	$4.3	$4.5	$3.4	$4.7
Cargo	$4.3	$4.5	$5.2	$6.7

On a cost-per-pound basis for Summit deliveries, GrIT12 was more expensive than airlift for fuel delivery but less expensive for cargo. Relative to airlift, the larger GrIT14 season achieved similar cost per pound for fuel delivery and significantly less cost per pound for cargo delivery. Excluding capital costs decreases delivery costs per pound for both modes by about 20%.

Table 12 summarizes the 2012 and 2014 total delivery costs for GrIT, accounting for the specific mix of fuel and cargo deliveries made. The table also shows the corresponding airlift costs that would have been incurred to deliver the same payloads. The net annual economic benefits from GrIT are the differences between airlift and GrIT total costs for each season, and the corresponding benefit/cost (B/C) ratios are the ratios of airlift to GrIT costs. These calculations follow the standard approach to compare a new investment with the status quo (Grant et al. 1982): offset airlift costs are treated as benefits to GrIT's operation. As noted, the analysis for 2012 explicitly accounts for the GrIT12 deliveries to NEEM. Whether capital costs are included or excluded, GrIT12 essentially broke even while the larger GrIT14 saved about $500,000. The calculated B/C ratios for GrIT increase when we exclude capital costs for both modes. GrIT12's deliveries to NEEM increased its B/C ratio because airlift costs are proportionally higher owing to longer flight times and lower ACL than flights to Summit.

Table 12. 2012 and 2014 total delivery costs, net annual economic benefit, and benefit/cost ratio for GrIT compared with airlift.

	GrIT Cost to Deliver Payload		Airlift Cost to Deliver Payload		GrIT Net Annual Benefit (Cost)		GrIT Benefit/Cost	
Analysis	2012	2014	2012	2014	2012	2014	2012	2014
Capital Included	$1,563,000	$2,347,000	$1,554,000	$2,825,000	$(9,000)	$478,000	0.99	1.20
Capital Excluded	$1,202,000	$1,826,000	$1,237,000	$2,402,000	$36,000	$576,000	1.03	1.32
LC-130 Capital Excluded	$1,563,000	$2,347,000	$1,314,000	$2,516,000	$(249,000)	$170,000	0.84	1.07

Table 12 also shows results from an analysis specifically requested by NSF-RSL: include GrIT capital costs but omit capital costs and upgrade and overhaul costs for the LC-130 fleet. This analysis reflects RSL's perspective that it will purchase new GrIT capital equipment (e.g., tractors) as needed but that it does not expect to contribute to LC-130 replacement or overhaul as the aircraft reach the end of their useful lives. From this perspective, GrIT12 lost money, but the larger GrIT14 saved RSL $170,000.

6.2 Incremental benefits from efficiency gains

GrIT is a relatively recent alternative to airlift resupply of Summit Station. We expect that GrIT's efficiency of operations will improve as the mode matures. Sled efficiency improvements in particular would have a large impact on GrIT's economic performance. A useful measure of sled efficiency is payload weight carried per unit towing force required; higher is better. By this measure, the newly developed ARCS are about 70% the efficiency of fuel-bladder sleds (Lever et al. 2016). Through research cooperatively supported by the South Pole Traverse, we expect that the performance of ARCS will approach that of bladder sleds. GrIT could benefit from this improvement by either delivering more payload for the same fleet effort (fuel consumption, in-field transit time) or by reducing the fleet effort to deliver the same payload. For example, if GrIT14's ARCS had been able to carry 20% more payload for the same tractor effort, net benefits in 2014 would have increased by $330,000.

We are actively pursuing this efficiency gain. Assuming RSL's share of the required R&D investment will be about $100,000, payback on a single traverse comparable to GrIT14 will be 3:1. Each successive traverse using the efficient ARCS will boost the payback on this R&D investment.

6.3 Oversized and overweight cargo

GrIT can achieve benefits over LC-130 airlift beyond cost-per-pound savings. The most important quantitative benefit derives from the capability of ARCS to deliver oversized cargo safely and smoothly. Near-term examples include the new Atmospheric Watch Observatory (AWO), large components of the Greenland Telescope (GLT), and prefabricated buildings for Isi Observatory and its support camp.

The LC-130 cargo bay has maximum usable dimensions of 8.8 ft wide × 8.5 ft high × 39 ft long. The LC-130 weight limit (ACL) for Summit flights is 21,100 lb. Payloads that exceed either limit must be flown as partial assemblies and then reassembled at Summit. Cost savings using GrIT to transport fully assembled payloads would include no-cost sealift staging to Thule, versus C17 staging to Kanger, and low-cost stateside or Thule assembly, versus airlift of materials and high-cost Summit assembly. Moreover, GrIT enables the delivery of large, complex items that cannot feasibly be subdivided to satisfy the size or weight limits of an LC-130 (e.g., Greenland Telescope main dish).

6.4 Air emissions

Lever and Weale (2011a) estimated reductions in air emissions for the proposed GrIT compared with LC-130 airlift to resupply Summit Station. They based their analysis on the *Comprehensive Environmental Evaluation* prepared by NSF to assess potential environmental impacts of Antarctic traverses (NSF 2004). Lever and Thur (2014) repeated this analysis for SPoT's actual payloads delivered and fuel consumed over the three operational seasons 2008–11. Both analyses showed similar results: GrIT and SPoT offer impressive emissions reductions in the five air emissions analyzed (sulfur oxides, nitrogen oxides, carbon monoxide, exhaust hydrocarbons, and particulates). The main reductions result from two orders-of-magnitude lower emissions per unit fuel consumed. The turbo-diesel engines in GrIT's tractors are much cleaner per gallon of fuel burned than the turboprop engines in LC-130s.

Secondary emissions reductions derive from lower GrIT fuel consumption to deliver the same payload relative to LC-130 delivery. Table 13 compares GrIT and airlift fuel consumption to deliver the 2012 and 2014 GrIT payloads. Note that the fuel consumed for skiway maintenance is small relative to LC-130 consumption. The airlift figures do not include fuel for C17 cargo staging to Kanger; that consumption would be much larger than cargo staged by sealift for GrIT.

Table 13. Fuel consumed by GrIT12 and GrIT14 compared with airlift delivery of the same payloads (see Table 1 for payloads delivered).

Year	GrIT Consumed (gal.)	GrIT (lb-consumed/lb-delivered)	LC-130 Consumed (gal.)	Skiway Consumed (gal.)	Airlift (lb-consumed/lb-delivered)
2012	17,100	0.43	48,700	2300	1.3
2014	25,700	0.45	63,300	3200	1.2

GrIT consumes only 40% of the fuel required for airlift delivery of the same payload. This drops GrIT's air emissions to less than 1% that of airlift delivery. Furthermore, lower fuel consumption means that $C0_2$ emissions are 60% lower for GrIT than for airlift delivery.

Air emissions near Summit are of particular concern because clean air and snow sampling account for much of the scientific activity conducted near the station. Each LC-130 flight burns about 3300 lb (470 gal.) of fuel during taxi in, cargo transfer, taxi out, and one takeoff slide (Lever and Weale 2011a). For both 2012 and 2014, GrIT's fuel consumption within 10 miles of Summit was less than 10% that of the LC-130 near-Summit consumption for the flights offset. In fact, GrIT's fuel consumption near Summit was only 20% of that for annual skiway construction and maintenance. Overall, GrIT's air emissions near Summit were less than 0.1% that of airlift near-Summit emissions for the flights offset.

6.5 Field science opportunities

GrIT's safe route and resupply capabilities have enabled science projects to be conducted in remote areas of the Greenland ice sheet (Figure 1). GrIT can stage equipment and supplies for these projects, and it can offer mobile infrastructure for science traverses able to operate at a similar daily advance rate.

However, science projects can inadvertently impose extra costs on GrIT relative to its role as a resupply traverse for Summit. For example, to stage supplies for the SAGE project, GrIT altered its outbound route in 2014 to pass south and east of NEEM. They encountered much softer snow and hence worse mobility conditions than along the 2010–12 routes. This probably caused extra field time and fuel consumption from shuttling loads and thus higher costs to GrIT14. Nevertheless, assuming that GrIT's incremental costs can be estimated, RSL can balance cost increases against the program value GrIT generates to support specific science projects.

7 Cost of Fuel Delivered to Summit

Beyond an economic analysis of GrIT, RSL also requested analysis of the cost per gallon of fuel at Summit, which is of special interest when considering investments in renewable energy technologies for the station. The cost of fuel at Summit derives directly from the costs identified within this report. Table 14 summarizes fuel costs at Summit for GrIT and airlift delivery modes. Component costs include the fuel purchase price, cost for delivery to Summit, and storage and transfer costs. On-site renewable energy production could offset these costs. Fuel is clearly an expensive commodity at Summit regardless of how it is delivered.

Table 14. Fuel cost per gallon at Summit, averaged across 2012–14.

Analysis	2012–14 Average Price ($/gal.)	Average Delivery Cost ($/lb)	Average Delivery Cost ($/gal.)	Fuel Storage and Transfer ($/gal.)	Total Delivered Fuel Cost ($/gal.)
Capital Included					
Airlift	$4.4	$5.1	$35.5	$1.5	$41
GrIT	$3.7	$5.7	$39.9	$1.5	$45
Capital Excluded					
Airlift	$4.4	$4.0	$28.3	$0.2	$33
GrIT	$3.7	$4.4	$30.8	$0.2	$35

8 Discussion and Conclusions

We have compiled here the deliveries and costs of GrIT12 and GrIT14 to assess its economic performance relative to airlift to resupply Summit and NEEM. We have treated offset airlift costs for delivered cargo as benefits to GrIT. GrIT's deliveries and costs are straightforward to compile because it operates as a stand-alone activity. Airlift costs are more diffuse with airlift support spread across the Arctic RSL program. Beyond the SAAM rate (cost per flying hour), the cost to position LC-130s in Greenland, to stage cargo via C17, to operate Raven, and to construct and maintain the Summit skiway are all significant contributions to the total airlift cost. Because fuel is expensive at Summit, fuel use constitutes over half of the cost to construct and maintain the skiway.

As with any economic analysis, the overall outcome depends on the underlying assumptions in the cost model. If we compare GrIT and airlift deliveries on a common cost-per-pound basis, and either include or exclude annualized capital costs for both modes, GrIT12 essentially broke even while the larger GrIT14 saved about $500,000 (Table 12). On the other hand, if we assume that RSL will eventually replace GrIT's capital equipment but will not contribute to LC-130 replacement or overhaul, GrIT12 lost about $250,000 while GrIT14 saved $170,000. The larger scale and an extra season's experience probably account for the better economic performance of GrIT14 relative to GrIT12, regardless of the cost model used.

Interestingly, GrIT has a cost advantage for cargo delivery to Summit and a disadvantage for fuel delivery, despite the current efficiency advantage of bladder sleds over ARCS. Cargo staged to Kanger costs about $2/lb using C17 airlift, the most economical staging mode. Because two-thirds of GrIT's 2014 delivery was cargo, offset staging costs provided significant benefits to GrIT14. Similarly, GrIT12's benefits were enhanced by the relatively higher cost to airlift fuel to NEEM, owing to lower ACL and longer flying times compared with Summit. In some sense, these relative advantages reflect GrIT's versatility as a delivery mode and allow RSL to optimize the total Greenland annual resupply effort by apportioning payloads between GrIT and airlift.

GrIT's advantage for cargo delivery will likely gain importance as Summit modernizes and expands to include AWO, Isi Observatory, and the GLT. Large cargo items will dominate Summit deliveries. These facilities could be prefabricated in the United States, sealifted at no charge to Thule, and transported on ARCS to Summit. For example, AWO could be partially pre-assembled by adding the exterior panels and telescoping legs to its welded space frame, work that crews would otherwise need to complete under more demanding and expensive conditions at Summit. Similarly, modules for Isi Observatory and the GLT support camp could all take advantage of lower-cost prefabrication and GrIT delivery. Importantly, the major components of the 12 m GLT are too large for airlift by LC-130. GrIT is currently the only feasible mode to deliver them to Summit.

GrIT's future role in cargo delivery reinforces the need to enhance the efficiency and reliability of ARCS. GrIT, SPoT, and CRREL are actively collaborating in this effort. As with bladder sleds, which are only a few years more mature, we expect a modest R&D investment will extend the life and increase the efficiency of ARCS by identifying more durable materials, simplifying construction, and optimizing ground pressure and payload-weight distribution. GrIT, and hence RSL, will realize a large payback on this investment.

GrIT's modest economic performance stands in contrast to SPoT's, which provides substantial economic benefits relative to airlift deliveries to South Pole (Lever and Thur 2014). However, GrIT at its peak in 2014 had only about half the towing capacity of a SPoT fleet and indeed delivered 52% of the average 2008–11 SPoT deliveries. GrIT must therefore spread its crevasse-mitigation, staging, project-management, R&D, and fleet-support costs over half of the delivered payload. Economies of scale favor SPoT.

The most significant non-economic (intangible) benefit of GrIT relative to airlift derives from its much lower air emissions to deliver the same payload. In particular, GrIT's emissions in the vicinity of Summit are less than 0.1% of the offset airlift emissions near Summit. Although difficult to monetize, much of Summit's science mission relies on clean air and snow sampling. GrIT's emissions reductions directly contribute towards that mission.

We have run parallel cost analyses to either include or exclude annualized capital costs. Capital costs are slightly more significant for GrIT than for the airlift, so GrIT benefits more from their exclusion. We think including capital costs more faithfully reflects steady-state economic conditions, where assets are replaced periodically according to their expected useful lives. However, it is unclear the extent to which NSF in general and RSL in particular are exposed to costs to replace NSF's four LC-130s. Nevertheless, these aircraft are 20–30 years old, and even excluding their eventual replacement, escalating repair, overhaul, and upgrade costs represent significant cost risks to NSF and hence RSL. GrIT represents a hedge to these risks.

As analyzed, the economic benefits of GrIT derive from offset airlift costs. Given the need to position at least three LC-130s in Greenland for each flight period, perhaps the best way to capture these benefits is to reduce the number of flight periods. Indeed, USAP now plans for and executes fewer annual LC-130 flights to South Pole, reflecting SPoT's role as a reliable and less expensive alternative. GrIT's benefits will increase if it preferentially transports construction materials, prefabricated facilities, and oversize cargo associated with Summit modernization, Isi Station, and the GLT. The analyses presented here should help to optimize the balance between airlift and GrIT annual deliveries to Summit.

An important assumption made in the present analysis was that airlift costs scale linearly with usage. Examples of usage include on-island flying hours, Summit flights, and payload weight staged to Kanger. We made this assumption to simplify the calculation of offset airlift costs to claim as benefits for GrIT. In fact, actual airlift costs are likely to be nonlinearly related to usage by having both fixed- and variable-cost components. The present analysis helps to identify the major cost drivers (e.g., LC-130 positioning costs and C17 cargo staging) that warrant more detailed investigation into their dependence on usage.

Similarly, SCAT represents an important cost driver for GrIT that also varies nonlinearly with the scale of GrIT's delivered payload: SCAT's costs are largely fixed if GrIT undertakes any deliveries. The costs for SCAT should be separately identified within GrIT's costs to quantify how operational changes and technology improvements in crevasse detection and mitigation could help reduce GrIT's overall costs.

GrIT is still a relatively new transport mode to deliver fuel and cargo to Summit Station. The improved economic performance of GrIT14 relative to GrIT12 suggests that efficiencies related to scale and experience are important. Furthermore, it is likely that GrIT's costs will decrease and payload efficiency will increase over the next 2–5 years as we improve the design of its cargo sleds. These factors all bode well for GrIT's future economic performance relative to airlift. Nevertheless, GrIT as currently configured can make modest cost savings relative to LC-130 airlift. Likely efficiency gains, reduced emissions, and its ability to deliver critical oversized cargo make GrIT extremely attractive as an ongoing resupply mode for Summit Station.

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14. ABSTRACT

The Greenland Inland Traverse (GrIT) transports fuel and cargo over snow to resupply science stations on the Greenland ice sheet from Thule Air Base. GrIT offers an alternative to the traditional LC-130 airlift resupply from Kangerlussuaq, Greenland. In this report, we assess the economics of GrIT relative to airlift resupply operations by comparing the costs of each mode to deliver the same fuel and cargo based on data from the 2012 and 2014 seasons.

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