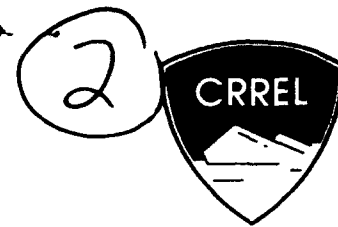


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Delivery of Fuel and Construction Materials to South Pole Station

Stephen L. DenHartog and George L. Blaisdell

July 1993

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Abstract

Plans are underway to rebuild South Pole Station, ideally with minimal impact on the current science and operational program. The new station will require the delivery of massive amounts of construction materials to this remote site. The existing means of delivering material and fuel to the South Pole include the use of specialized and rare LC-130 Hercules aircraft that can operate on wheels or skis, and some materials are also air-dropped from C-141 aircraft. Neither of these delivery systems is expected to be capable, within a reasonable time period, of supporting both current operations and the transport needs for construction of a new station. Several options for moving construction materials and fuel to South Pole Station are analyzed. All of our options assume that goods will be transported to the Antarctic continent by ship. The options include a) construction of a snow runway at the South Pole capable of supporting wheeled aircraft, b) development of an inland blue-ice runway capable of supporting heavy wheeled aircraft, located as close as possible to the South Pole, with over-snow vehicle haulage from the runway to the Pole (two potential sites are considered), c) over-snow vehicle haulage from McMurdo across the Ross Ice Shelf, up the Skelton or another glacier, and over the polar plateau to the Pole, and d) vehicle haulage from some coastal station (located at about 6° S latitude) with an easier access route onto the polar plateau. Pros and cons of these options are discussed and issues associated with each are identified. The feasibility and risk associated with each option are covered as well. Estimates of costs for many of the factors involved with each option allow financial comparison of each delivery scheme. Ultimately, the results of this study are probably best used as a starting point for any serious planning and budgeting for the development of a new South Pole Station.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380-89a, *Standard Practice for Use of the International System of Units*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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Special Report 93-19



**US Army Corps
of Engineers**

Cold Regions Research &
Engineering Laboratory

Delivery of Fuel and Construction Materials to South Pole Station

Stephen L. DenHartog and George L. Blaisdell

July 1993

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PREFACE

This report was prepared by Stephen L. DenHartog, Civil Engineer, Ice Engineering Research Branch, and George L. Blaisdell, Research Civil Engineer, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The project was funded by the National Science Foundation Division of Polar Programs under contract no. OPP-91-40015.

The authors wish to thank Nicholas Collins, Wayne Tobiasson, and Paul Sellmann of CRREL for technically reviewing the report.

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Delivery of Fuel and Construction Materials to South Pole Station

STEPHEN L. DENHARTOG AND GEORGE L. BLAISDELL

INTRODUCTION

The United States Antarctic Program (USAP) is planning to rebuild portions of the existing South Pole Station and add satellite facilities there as part of its science program expansion. Except for delivery of some construction equipment by parachute from C-141 aircraft, all resupply to the South Pole since the early 1960s (including cargo, food, fuel, and passengers) has been performed by LC-130 aircraft. These specialized, ski-equipped aircraft can deliver about 22,000 lb to the South Pole with each trip. Round-trip flight time from McMurdo is nearly 6 hours. As the load requirements grow and the National Science Foundation fleet of six LC-130 aircraft ages, another means of resupply will be necessary. This could include greater use of the four LC-130s owned and operated by the New York Air National Guard.

Based upon a number of assumptions, we have analyzed several delivery system options. These options were originally proposed at a workshop dedicated to a systems approach for planning a new South Pole station (Capital Systems Group 1992). For each option, we have attempted to figure the actual cost to the USAP as it exists today (i.e., we charged only for new personnel, facilities, equipment, and services that are not present now). The options we consider include

- a) producing a snow pavement at the South Pole sufficient to allow operation of wheeled aircraft,
- b) flying cargo on wheeled aircraft to an inland blue-ice site (specifically Mt. Howe or Mill Glacier) and surface hauling from there, and
- c) direct over-snow delivery from McMurdo via the Skelton Glacier or some other coastal station (picked arbitrarily to be located at 67°S).

We also discuss the feasibility of each of these options; none has yet been proven.

A certain degree of risk is associated with each of the considered delivery options. Any comparison of these options must give serious attention to real or perceived danger to personnel and equipment. In addition, environmental impact must be considered. cursory examination of risk and environmental impact are included in this study.

BASELINE INFORMATION

This study includes three areas of consideration: feasibility, cost, and risk. Our comments regarding feasibility are based primarily on current operational capability and historical experience. To perform cost calculations and complete fair comparisons of the various delivery options, agreement on a number of factors was required. In most cases it was easy to derive or obtain these factors, but in some cases it was necessary to make assumptions or to choose values arbitrarily. Risk assessment was performed qualitatively based on our concept of each delivery scenario.

Overland transport

Since few long traverses have been done in recent years in Antarctica, modern heavy-haul traverse vehicles have not developed over the recent past. (Refer to the section on *Feasibility* for a discussion of historical traverses.) The Australians have produced a super-modified Caterpillar LGP (low ground pressure) D7 (Fig. 1) specifically for traversing, and reports are that it works quite well. This tractor is still quite slow, with a top speed of about 6 mph. A similar concept for a super LGP D7 has been developed by Caterpillar and the Naval Civil Engineering Laboratory (Barthelemy 1988).



Figure 1. Australian super low ground pressure (LGP) D7 Caterpillar traverse tractor.

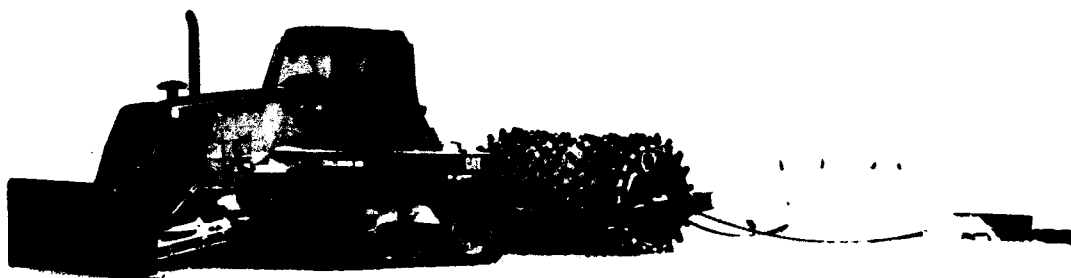


Figure 2. U.S. antarctic-equipped Caterpillar Challenger tractor.

The U.S. Antarctic Program has performed over-snow tests (Blaisdell and Liston 1990) with the Caterpillar Challenger tractor (Fig. 2) and now has two such tractors in the McMurdo area. The Australians (Sheers 1992), the South Africans (deWet 1992), and the French (Laffonte and Gordon 1991, 1992) are also using Challenger tractors in Antarctica. These tractors are mostly stock and show great promise for long traverses because of their high speed (18 mph) and relatively comfortable ride due to a suspended rubber track system. The 38,000-lb Challenger (4.9 psi ground pressure) does not have as high a drawbar pull as a D7, but a force of 16,000 lb can be generated on snow at low speeds and up to 3000 lb at full speed. We have been working with Caterpillar to develop

a special traverse version of the Challenger. This tractor would have an extended track length to increase towing ability and provide a more comfortable ride. It would also have an extended cab to allow one or two passengers to ride along.

Since no firm data are yet available for the long-track Challenger, we assumed for this study that the standard turbocharged Challenger tractor would be used for all traversing. A travel speed of 8 mph was estimated as comfortable and sustainable under most snow conditions (based on our experience with the tractor) with a drawbar pull of 11,000 lb at this speed.

Both sleds (Fig. 3) and tracked trailers (Fig. 4) were considered as possible towed units to move cargo. Modern sleds have a weight of about 16,000 lb empty,

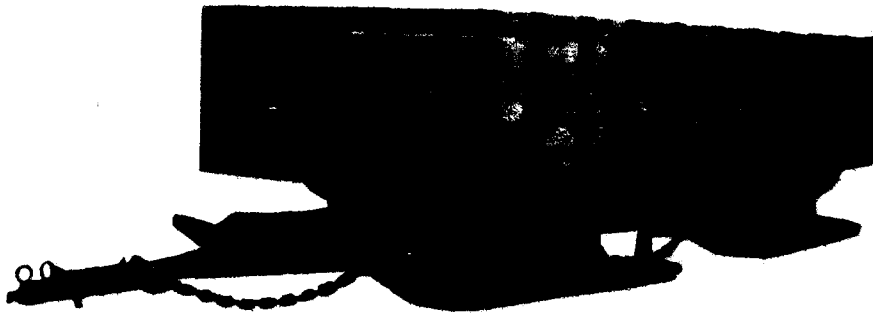


Figure 3. Aalener 20-ton sled.

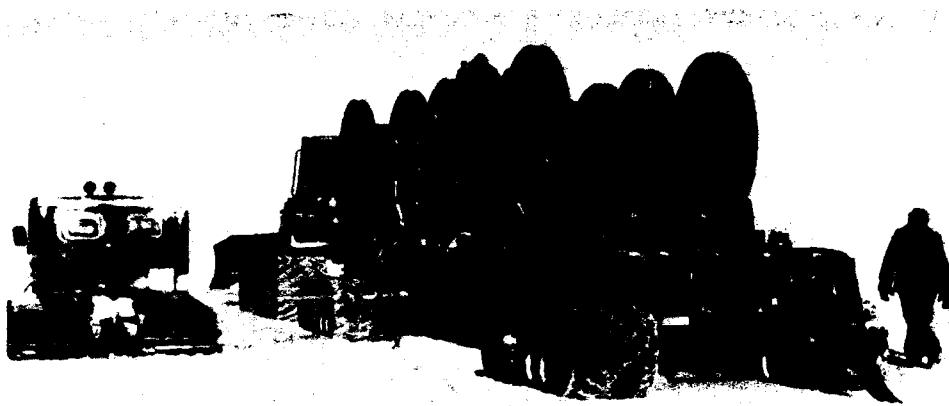


Figure 4. U.S. Caterpillar/Fruehauf 25-ton tracked trailer with retractable roller deck.

a deck size of 9×21 ft, a load capacity of 40,000 lb, and a sliding resistance coefficient of between 0.08 and 0.15, depending on surface type (soft or wind-blown snow, ice). Tracked trailers were estimated to weigh 18,000 lb empty, have a deck size of 9×50 ft, a load capacity of 50,000 lb, and a rolling resistance coefficient of between 0.08 and 0.13, depending on surface conditions (Blaisdell 1992).

A significant difference between sleds and tracked trailers is the force required for start-up. Skis on sleds freeze to the surface when parked for more than a few minutes, and often a large force or an impact load is required to shear the interface bond and start the sled in motion. Even when not frozen to the surface, a tractor must overcome the static friction coefficient (often significantly higher than the sliding friction coefficient) to start a sled moving. Thus, it is common to have slack built in to the tow cables or tow bars on sleds to allow the tractor to impart an impact to the sled and start each sled moving independently (similar to a locomotive starting a train of rail cars in motion). Tracked trailers, on the other hand,

often do not freeze in place when parked. In addition, they are much easier to start in motion because of the "walking" action of the track that lifts the track up off the surface.

For this study, we assumed that most of the traverse will be on the polar plateau where much of the snow surface is windblown and firm. Our brief experience with the tracked trailer in Antarctica indicates that, compared to a sled, a lower towing resistance coefficient was present for snow with densities less than 0.35 g/cm^3 . On firm snow (density between 0.4 and 0.55 g/cm^3), the towing resistance coefficient for sleds and trailers was about equal. On ice or very compact snow surfaces (virtually no ski sinkage), the sled showed a slightly lower towing resistance coefficient. Without more information, we felt that it was fairest to apply the same towing coefficient for sleds and tracked trailers. A value of 0.09 was assumed.

Each empty sled requires a drawing force of 1440 lb. One fully loaded sled would take 5040 lb to move; two loaded sleds (with a total payload of 80,000 lb)

require 10,080 lb of drawbar force. Considering the 11,000-lb pull available from the tractor at speed, an additional payload of 10,200 lb could be towed. However, this would require an additional towed unit, which, even empty, would probably use up this tractive reserve.

An empty trailer requires 1620 lb to pull on typical polar plateau snow. One fully loaded trailer (50,000-lb payload, 6.8 psi ground pressure) would use up 6120 lb of available drawbar force and a second trailer could carry a payload of 36,200 lb before the tractor's drawbar capacity is exceeded, yielding a gross payload of 86,200 lb. Thus, each tractor could tow two trailers and move about 86,000 lb of cargo with the trailers operating at 86% of their rated load. In the case of sleds, a gross payload of 80,000 lb could be moved on two sleds (the sleds operating at their load limit).

Air delivery to inland transfer point

For the delivery scenarios that involve aircraft and tractor-trailer trains, we assumed that cargo would remain on aircraft pallets when transferred from the airplane to the towed units. To do otherwise would add a tremendous amount of labor at the transfer point. Aircraft pallets, we understand, are approximately 9×7.3 ft and have a load limit of about 4500 lb. Thus, each tracked trailer would have seven pallet positions. Loaded with seven aircraft pallets, a total of 31,500 lb per trailer results. This represents only a 63% utilization of the trailer's capacity. With a 49,500-lb gross weight for each of two trailers, only 8900 lb of the tractor's 11,000-lb drawbar capacity is used to deliver 14 pallets. Unfortunately, addition of a third trailer by itself (empty) would use up nearly all of this tractive reserve. Thus, the 2100 lb of extra tractive force might best be used to sustain a higher ground speed.

Each sled would have space for three pallets, yielding a total load of 13,500 lb. This is well below the load limit (34% utilization of rated payload). A total of four sleds could be towed, each with three 4500-lb pallets. This would require 10,620 lb of the tractor's towing force; the remaining 380 lb of available drawbar force could probably only be efficiently used to attain a slightly higher speed. Thus, with four sleds, a maximum of 12 pallets could be delivered by each tractor. In this scenario, most of the tractor's drawbar capacity is used up in towing the sleds themselves rather than the payload.

In short, when confining all of the payload to aircraft pallets, the full capacity of neither trailers nor sleds is utilized. And, because we are restricted to multiples of sleds or trailers, the tractive force of the

tractor is not ideally matched either. Each tractor-trailer would be required to carry its own fuel, some repair parts, and a wannigan. These items could be used to "round out" the load, but it would probably be at the expense of pallet positions.

A possible means to better utilize the full potential of the over-snow transport system would be to deliver fuel to the South Pole Station in conjunction with movement of construction materials. All fuel for the station is now delivered by aircraft. This is a tremendously expensive and inefficient method of delivery. The tractor-trailer is ideally suited for delivering fuel. By mounting tanks that do not interfere with the deck on the sleds or trailers, fuel could be used to "top off" each trailer or sled load.

Traverse time

We calculated a 20-hr travel day for the overland transport from the inland stations. This is only an estimate of an average expected traverse. Most of the terrain covered is level and, after the first few trips, the route would be familiar to operators. In addition, the longest trip from an inland station is only about five days, so it seems plausible that this schedule could be maintained.

The 2376-mile round-trip from McMurdo, or 3036-mile round-trip from a coastal station, is quite a different matter. We figured this on a 12-hr travel/12-hr rest and maintenance schedule. The crew would probably operate more hours per day than this; however, for segments of the trip an 8 mph average speed is not sustainable (e.g., up the Skelton Glacier). For estimation purposes, we assumed an 8-mph speed for 12 hours per day. This results in a 26-day round-trip from McMurdo or 33-day round-trip from a coastal station. Thus, three round-trips per year are possible from McMurdo or two complete circuits from a coastal station.

Aircraft and blue-ice runway details

The LC-130 aircraft, currently used for most USAP needs, were not considered for use in this study. This is principally because these aircraft are in short supply, have a lower maximum payload than a standard C-130 (due to the addition of skis), and are fully utilized supporting the science and everyday logistics needs of the Antarctic Program. In addition, all of the scenarios that are considered here involve aircraft landing on surfaces that will support wheels, so conventional aircraft can be used.

The primary cargo aircraft in the U.S. military system are the C-130 and the C-141. The C-130 is attractive because of its ability to operate on relatively rough terrain and its moderate tire pressure (95 psi).

However, it is propeller-driven (slow) and has a maximum payload of only about 30,000 lb or six pallets. The C-141 has a payload of more than 60,000 lb with 13 pallet positions and, being jet propelled, travels much faster than the C-130. Unfortunately, the C-141 is designed to operate only on nearly ideal runways (very low wing tips, very high tire pressures, very little under-belly clearance).

Structurally, an inland blue-ice runway in Antarctica could most likely support any type of aircraft operations. The ice on a given site may need some smoothing to remove bumps and swales, and the runway must be sited to avoid any crevasses in the area. The ice itself at such a site would have adequate strength and a surface friction coefficient high enough for safe operation of aircraft. However, considering the combination of factors present at an inland blue-ice site (e.g., surface roughness and friction coefficient, runway length requirements, winds, air temperature, geographic obstacles), only aircraft designed for rough field, tactical operations should be considered for use.

A compacted snow runway at the South Pole is currently used by ski-equipped LC-130s. Strength measurements on this runway indicate that it could support tire pressures of about 35 psi. At some locations at the South Pole strength measurements have shown that snow can be made to support loads in the range of the C-130 tires. These have been relatively small areas compared to a full runway and taxi and parking area. Further study is required to determine

- a) what equipment is best suited for processing a large area,

- b) what time and sequence of events will maximize strengthening of the snow,
- c) how long it will take for the processed snow to reach the required strength,
- d) how much areal variability in processed snow strength is to be expected,
- e) how much annual maintenance would be required once a strong snow pavement is produced, and
- f) how much deterioration in the runway will be caused by the operation of wheeled aircraft.

Infrastructure

Most of the infrastructure required at South Pole Station and at McMurdo for any of the proposed delivery options already exists. Some augmenting of equipment and structures may be necessary. Depending on the site chosen for the take-off point for a coastal station-to-South Pole traverse, considerable infrastructure may be required. Housing, maintenance, storage, and cargo handling facilities will be required, as well as a ship off-loading capability.

At any inland site, a camp to house six or possibly more people will be necessary. For fire safety, at least two heated buildings should be present on-site. The existing 8 x 20-ft six-bunk hut at Mill Glacier is confining, but it would be comfortable quarters for four with space for two temporary guests. Two buildings of that size and configuration for bunking and a third for office/aircrew/radio, etc. would be adequate. In addition, an inland site would need at least minimal facilities for maintenance and winter storage of equipment.

All buildings that would be placed on snow or ice surfaces should have allowances for problems related to ablation and snow drifting. They could either be placed on columns or skids.

Equipment for loading and unloading cargo will be required at McMurdo, the South Pole, and at any inland transfer points or coastal station depending on the delivery option chosen. For this study, we assumed that a "K" loader type vehicle (Fig. 5) would have to be purchased for the South Pole if the direct air option is



Figure 5. U.S. Air Force "K" loader.

Table 1. Additional required infrastructure.

<i>Delivery option</i>	<i>Structures</i>		<i>Equipment</i>	
Direct air	Equipment shelter at South Pole Station	(\$75K)	"K"-type loader Tractors (2) Processor Tracked loader Rollers (2)	(\$250K)* (\$350K) (\$250K) (\$200K) (\$160K)
Via Mt. Howe	Berthing Equipment garage Material storage racks Fuel storage	(\$125K) (\$75K) (\$50K) (\$50K)	"K"-type loader Wheeled loaders (2) Utility truck	(\$250K)* (\$300K) (\$25K)
Via Mill Glacier	Berthing Equipment garage Material storage racks Fuel storage	(\$100K) (\$75K) (\$50K) (\$50K)	"K"-type loader Wheeled loaders (2) Utility truck	(\$250K)* (\$300K) (\$25K)
Overland from McMurdo	Equipment shelter at South Pole Station	(\$75K)	Tracked loaders (2, South Pole), Wheeled loaders (2, McMurdo),	(\$400K) (\$300K)
Overland from coastal station	New construction or upgrade of existing structures at coastal station	(\$500K)	Tracked loaders (2, South Pole), Wheeled loaders (4, coastal),	(\$400K) (\$600K)

*Could be actual "K" loader or other piece of equipment capable of receiving aircraft load.

chosen and for an inland site if an aircraft-to-tractor-trailer transfer would occur. An actual "K" loader is probably not appropriate for inland stations or the South Pole due to the adverse affect of cold temperatures on the vehicle's hydraulics. A tracked trailer could be configured to work in a similar fashion, however, for directly unloading an entire aircraft load. Several extra loaders would have to be added at South Pole Station and for an inland site or coastal station.

Table 1 lists the additional infrastructure we envision will be required under each delivery option.

PARAMETERS AND ASSUMPTIONS USED

The following listing summarizes the baseline information used for our analysis. We included delivery of all station fuel as part of our calculations.

1. Task

- 8,000,000 lb of material are needed to rebuild South Pole Station (construction material only).
- Delivery of 200,000 gal (1,374,000 lb) of fuel used at the station each season.

- For aircraft options, all loads are confined to USAF pallets (9 x 7.3 ft).
- Average load per pallet is 4500 lb.
- Delivery spread over four or eight seasons (two options).

2. Geography

- Mt. Howe is at 87°20'S, 176 surface miles from the South Pole.
- Mill Glacier is at 85°05'S, 330 surface miles from the South Pole.
- McMurdo to Mt. Howe is 630 nm (air).
- McMurdo to Mill Glacier is 440 nm (air).
- McMurdo is at 77°52'S, 728 nm by air from the South Pole (1188 miles via Skelton Glacier over-snow).
- Coastal station (67°S) to South Pole is 1518 miles over-snow.

3. Aircraft

- LC-130s not considered due to their limited number and reduced payload.
- C-141s not considered due to poor rough-runway potential.
- C-130 costs \$2789 per hour (includes crew, maintenance, and fuel).

- C-130 payload is 30,000 lb (pallets and deliverable fuel).
- C-130 average speed = 250 kt; up to 12 hr/day flying.
- Two round-trips per C-130 per day to any site.
- Wheeled flight season (WFS) is 1 Nov to 10 Dec = 40 days (32 flyable).
- 1.5 hours expected for load/unload operations for each flight.

4. Surface transport

- For short trips, a modern tractor-trailer can travel at 8 mph for 20 hr/day, yielding an effective rate of 6.67 mph.
- For long trips from the coast, 12 hr travel followed by 12 hr rest/ maintenance would be the norm, giving an effective rate of travel of 4 mph.
- Each tractor-trailer round-trip time includes a total of 24 hr for load/unload operations.
- A standard Antarctic Challenger tractor has a drawbar pull of about 11,000 lb at 8 mph; it can tow up to 122,000 lb gross load on tracked trailers or modern sleds on firm snow.
- Each tracked trailer is capable of carrying seven USAF pallets.
- Modern sleds are each capable of carrying three USAF pallets.
- Challenger cost is about \$200,000 (fitted for traverse).
- Tracked trailer cost is about \$100,000.
- Modern sled cost is about \$60,000.
- Challenger fuel consumption is 1.3 nm/gal, based on the French tests in Adelie Land (Laffonte and Gordon 1991, 1992).
- Tractor season from inland sites is 15 Nov to 30 Jan (approximately 60 days, allowing for several days off).
- Tractor season from McMurdo or a coastal station is 1 Nov to 30 Jan (approximately 80 days, allowing for several days off).
- Backup tractors and trailers will be required to assure that traverse schedules can be kept.
- For the short trips (via Mt. Howe or Mill Glacier), extra tractors and tracked trailers are budgeted, yielding a 50% reserve.
- For the long traverse option, one extra tractor and two extra trailers are budgeted for each five tractors needed.

5. Fuel

- JP8 = 6.87 lb/gal at \$0.70/gal.

FEASIBILITY

Direct air

We have already alluded to the fact that producing a compacted snow runway at the South Pole, while of great interest, is by no means a given. Many earlier studies have had as their goal the production of a strong snow runway for wheels at the South Pole (Barthelemy 1975, Barber et al. 1989, Lee et al. 1989, Abele 1990).

Strength tests at random locations on the existing skiway at the South Pole indicate that, at its weakest spots, tire pressures of no more than 35 psi can be supported now. Results from strength measurements on the snow mine road, and on a compacted snow pad prepared for a new building, indicate that strengths capable of supporting tires operating at 70 to 80 psi are possible. Discussions with Navy aircraft managers indicate that C-130 manuals allow tire pressures of 70 psi for operation on "unimproved sites." Under normal circumstances, concerns with low tire pressures center around heat build-up and potential failure of the tire-rim bead seal. Operating in Antarctica, on snow and ice runways, heat build-up is not a problem. With a tire pressure of 70 psi it is hoped that there would be no problems with the bead seal.

The high strength snow data at South Pole are for small areas. The runway, taxiway, and load/unload area represent about 4,000,000 ft² of surface. Whether the procedures and equipment used to generate the current strong snow surfaces can be used efficiently to process the huge volume of snow required to make a snow pavement (minimum 18-in. thickness), or if other techniques can be developed to address this construction problem, is yet to be shown. Thus, we feel that it is unwise to proceed with plans for direct air delivery using wheeled aircraft with tire pressures greater than 35 psi until a large-scale feasibility study demonstrates that snow at the South Pole can be processed to support wheeled aircraft.

It would seem that not enough is known at this time to rate the feasibility of this option. Thus, we would currently describe the feasibility of this option as "unknown."

Inland blue-ice locations

Studies of inland blue-ice sites, with the aim of using them as advance staging areas for South Pole-bound material, have been conducted by Mellor and Swithinbank (1989) and Swithinbank (1989). The emphasis of their work was on locating sites that were close to the South Pole and had clear, smooth natural ice surfaces of a size suitable for a large-air-

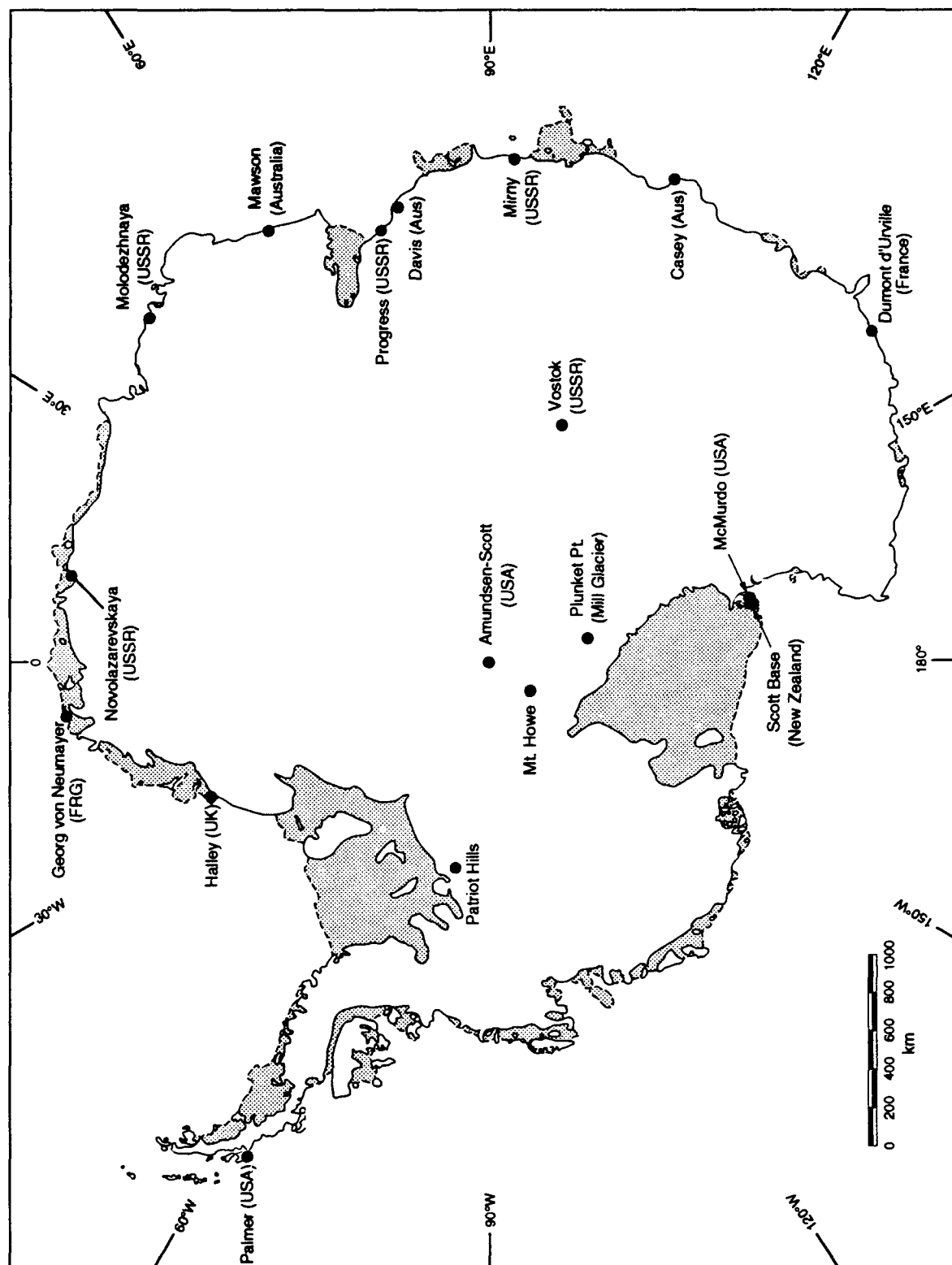


Figure 6. Map of Antarctica locating key sites.

craft runway. The two sites we consider in this paper, Mt. Howe and Mill Glacier (Fig. 6), are attractive because of (a) their relative proximity to the South Pole compared with other such sites, and (b) their position roughly along a line connecting McMurdo to the South Pole. Both sites have large expanses of blue ice that would require little or no preparation for landing of large, wheeled aircraft. In fact, LC-130s landed on wheels at Mill Glacier in 1989.

While the work to date on inland blue-ice sites is mostly encouraging, location and surface conditions are only two of the factors important to determining feasibility for use in delivering large quantities of materials to the South Pole. Two other factors—weather conditions at the site and the over-snow route to the South Pole—must be studied as well. Limited data are available for weather (in particular wind speed and direction) at either of the sites we have chosen to consider. What little experience is available suggests that wind speed is often high at both sites. During visits to Mill Glacier, the winds have most often been aligned roughly with the long axis of the protruding mountains and the surveyed runway, making aircraft approach and take off straightforward. A site visit to Mt. Howe during December 1991 documented winds aligned more perpendicular to the mountains and the most probable runway direction (DenHartog, 1993). Conversely, in January 1992, personnel installing an automatic weather station (AWS) at Mt. Howe reported the calmest day they had ever experienced on the polar plateau (C. Stearns, personal communication).

Several Twin Otter airplane trips to Mt. Howe have flown low over the route that would be traveled by tractor-trailers to deliver goods to the South Pole. Based only on observation, reports are that the route offers no great difficulties except for a 2- or 3-mile crevassed section near Mt. Howe (W. Tobiasson, personal communication). Analysis of video tape records of this area and multiple viewings from the air indicate that a safe route around this field is probable. The remainder of the route appears to have a surface of primarily firm snow with modest-sized sastrugi.

Recently, Reinhold Messner skied the South Pole to Mill Glacier route and reported no problems with snow surface or crevasses (Messner 1991).

Proving the feasibility of using an inland blue-ice transfer point will require establishing that a reasonable operating window exists with regard to wind conditions and that there is a driveable route between the site and the South Pole. In addition, the feasibility of operating a remote materials handling site (buildings, equipment) should be given some attention.

The feasibility of flying to a deep inland blue-ice site and hauling cargo over-snow from there to the South Pole seems "technically straightforward" to us, based on what is known at this time.

Over-snow traverse

Much of this paper hinges on surface transport across the Antarctic snowfields. Although there has been little of this recently, it was done extensively in the past. Old Byrd Station was built during the International Geophysical Year (IGY) entirely with goods delivered by tractor-trailers using Caterpillar LGP D8s (Fig. 7). Two of the original Byrd machines were driven across the snow to the South Pole station in the early 1960s. A large tractor-trailer also went from Little America V station to McMurdo in 1958–59 when that station closed. Some of these tractors are still in use in Antarctica today.

McMurdo to the South Pole

Over-snow travel from the Ross Ice Shelf up onto the polar plateau has favored use of the Skelton Glacier. The route up this glacier has been traveled many times by scientific parties (usually with light vehicles), starting with Sir Edmund Hillary using Ferguson farm tractors in 1957–58. Later, two par-



Figure 7. One of the original low ground pressure (LGP) D8 Caterpillar tractors used for traverses.

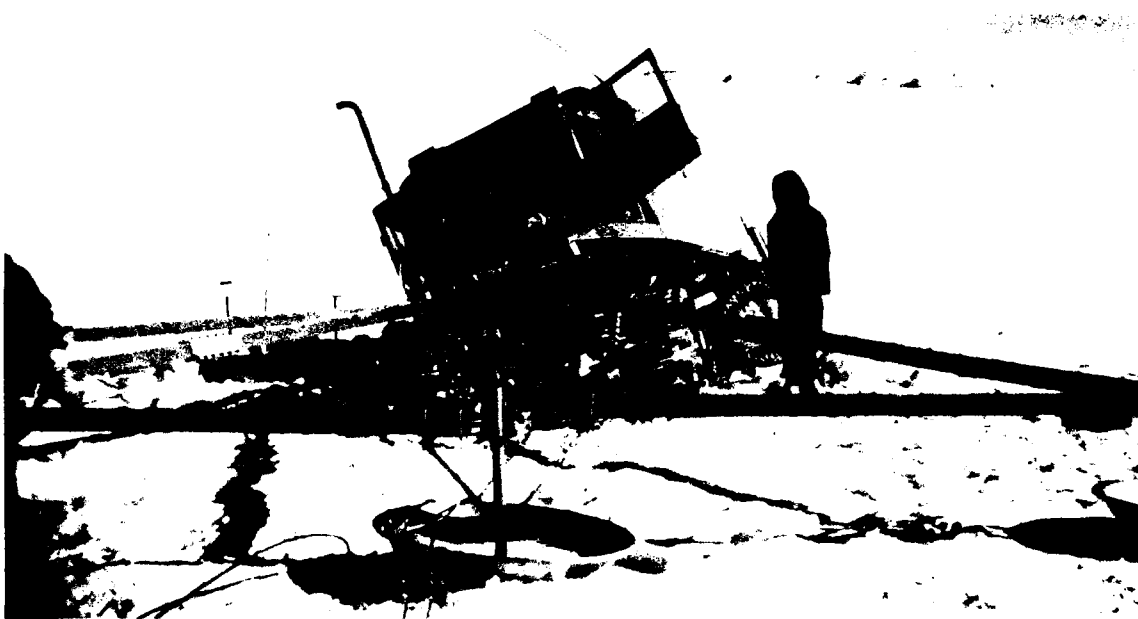


Figure 8. Tucker Sno-Cat (with device for crevasse detection mounted on front) in crevasse on Skelton Glacier in 1957.

ties went up the Skelton using Tucker Sno-Cat 743N machines in 1958–59 and 1959–60. During the 1960–61 season, this route was used again with Tucker 843s (Mellor 1963). Hillary had flagged a circuitous route through the crevasses near Twin Rocks and Stepside Spur. Later traverses followed his flags very closely, and yet several times they fell into small holes (Fig. 8) and came close to some very large cracks.

In recent years, traverses from McMurdo have primarily gone to Black Island (25 miles) and to Marble Point (about 60 miles). Repeated travel on these routes has brought confidence and an understanding of the surface and its vagaries. Occasionally, vehicles still fall into melt pools or have to significantly alter their route to avoid pressure ridges or other potentially disastrous obstacles.

A recent attempt to travel “cross country” on the Ross Ice Shelf southeast of McMurdo ended with a vehicle down in a crevasse within 40 miles of launch. The tractor-trailers always followed routes that had been scouted in some manner by personnel trained to identify dangerous terrain. We bring this matter up not to suggest incompetence in any way, but to emphasize the supreme ability of the Antarctic to disguise its treacherous nature, even from experts and experienced veterans. We feel that a traverse route from McMurdo across the Ross Ice Shelf, up the Skelton (or some other) glacier, and across the polar plateau to transport huge quantities of material with many tractors and people must be consid-

ered very seriously. Before the first traverse tractor is purchased, it would be prudent to scout, map, and mark this route. This is a formidable and dangerous task and will take considerable time. Since the terrain is dynamic, a safe route will not remain so forever. The route will require at least annual checking to ensure it is still safe.

We classify the feasibility of this option as “unlikely,” considering the rate of success in crevasse detection using current practice. We feel that one cannot give serious consideration to traverses from McMurdo to the South Pole without having a proven, reliable method of crevasse detection. The detection device should be able to be used with any vehicle and allow real-time feedback when operated at a reasonable speed. It must be able to operate in such a fashion that it allows ample time for a vehicle to stop when a void or gap is detected. We envision that a permanently assigned scout vehicle (perhaps more than one) would travel the traverse route or at least its most critical segments. The route would probably need to be marked with radar reflecting flags and be mapped using a Global Position System (GPS). Tractors would be equipped with on-board radar and GPS systems to allow precise navigation even when visibility is marginal, although travel during poor visibility is ill-advised whenever the surface is rough.

Tests in the 1992–93 season with a ground-based impulse radar may provide the level of confidence in crevasse detection necessary to upgrade the feasi-

bility of McMurdo to South Pole traverses. However, a means of efficiently applying this technology to the long traverse route would still be required.

Coastal station to the South Pole

The inland Russian station Vostok is supplied by tractor-trailers from the coastal station Mirny (Fig. 6). This train starts out in November with the goal of reaching Vostok by Christmas. The route is well marked and has been used for many years. We are unaware of any problems (e.g., crevasses, steep slopes) with the route. The tractors used are very large, old, and slow, and it is known that breakdowns are commonplace.

If a coastal launch point for a South Pole traverse is desired, use of the established route from Mirny to Vostok could be considered. This route covers roughly half of the distance to the South Pole and includes what is probably the most challenging portion. Having a well established route for half the journey and a "city" at the half-way point in the long traverse are very attractive features. However, we can find no information on the terrain between Vostok and the South Pole. Based on its location on the continent, this route is probably easily passable with a modern tractor-trailer and contains few, if any, crevasses or other obstacles.

It is doubtful that the current infrastructure at Mirny could support a ship-offload/tractor-trailer-onload operation of the size envisioned here. It would be necessary to study Mirny station and discuss with its operators what would be required to support this delivery scheme and how this could be accomplished. Members of the Russian Arctic and Antarctic Research Institute (AARI) in St. Petersburg have proposed the Progress station (Fig. 6) as a possible starting point. They claim this site has good port potential as well as a gentle rise up onto the plateau with few crevasses. Study of these stations, including specific negotiations with the Russians, will be required, along with reconnaissance of the traverse route as a next step in considering this delivery option.

We classify the feasibility of this option as "possible."

RISK

No serious consideration of any delivery option for South Pole Station can exclude a rigorous analysis of the risk involved. Such an analysis is beyond the scope of this paper, but we would be remiss not to at least review the obvious factors that must be

considered with respect to the delivery options discussed here.

We start with the presumption that ships would continue to deliver material and fuel to the continent and that the risks involved in this aspect of the operation are already well known.

Direct air

Flights to the South Pole take place on a regular basis from late November until late February each season. Around 150-170 flights are completed during this period. Aside from an increased number of flights, little difference would be expected in this operation if wheeled airplanes were included with the ski-wheel planes used at this time. Increased air traffic at McMurdo and the South Pole would certainly increase the odds of a mishap and might require improved tracking and flight control facilities. The risk to aircraft and flight-related persons would seem to be slightly increased with this option, but we consider the overall risk to be "low."

Inland blue-ice locations

As noted for the direct air option, increased air traffic will somewhat increase the risk of accidents. Air operations at inland blue-ice sites would involve landings and take-offs with few or no navigational aids. These sites also have nearby mountains and generally strong winds. The winds at such sites have not been studied, so little understanding of them currently exists.

Personnel living and working at an inland blue-ice site would be very isolated and thus their lives would be dependent on the facilities available at the site. The reliability of the infrastructure (including equipment) would be a great concern.

Tractor-trailers operating between a blue-ice site and the South Pole would travel over relatively benign terrain (by Antarctic standards), although temperatures and winds could often be extreme. Traveling in groups would seem prudent. It would be expected that storms would be infrequent on the polar plateau during the austral summer, and continuous daylight would also limit the danger. However, on-board navigation systems (as described above for the long traverses) and communications equipment would be essential. One-way trips between stations would take no more than 5 days, thus limiting exposure of tractor-trailer drivers. In addition, they would always be within easy reach by air, or even over-snow, for rescue from either the South Pole or the blue-ice station.

At least at the outset, we rate the risk involved with this delivery option to be "moderate."

Over-snow traverse

The obvious concern with this option is the very long (26 to 33 days) one-way driving time from McMurdo or the coast to the South Pole. During this period, operators and on-board mechanics will have for protection only their tractors and whatever wannigan they tow. Perhaps one-third of their trip will be near mountains or the coast, thus increasing the odds of being caught in storms. In addition, some of the terrain covered is known to be treacherous (crevasse-filled, steep slopes).

Tractor-trailer personnel will be very dependent on the reliability and accuracy of navigation and communication systems. During portions of their journey, personnel may be inaccessible to aircraft for rescue (on a glacier) or outside of radio contact of McMurdo or the South Pole. For nearly all of their journey, they will be outside reasonable rescue distance by surface vehicles. Traveling in groups would maximize safety.

The long exposure of personnel to the vagaries of weather with little protection, the long and dangerous nature of large segments of the terrain being traversed, the total reliance on mobile mechanical systems, and the long distance from safe havens make this option dangerous by almost any standard. Although it appears that using the route to and through Vostok would provide slightly less risk than a new route from McMurdo with no settlements en route to the South Pole, we consider this option to have a "high" risk factor.

ENVIRONMENTAL IMPACT

A separate but related issue is the environmental effect each of these options may have on the Antarctic continent. A thorough environmental assessment will be necessary for any option that proves to be feasible and is attractive from a cost and operations standpoint. At this stage of the analysis, however, a cursory examination of the delivery scenarios considered here does not indicate that any major environmental impact would be expected. In the case of the direct air and overland traverse options, cessation of operation for even one year would allow nature to reclaim any alterations in the terrain caused by construction and use. The impact of a small facility at an inland blue-ice site would be slightly greater. Assurance of continued integrity of a blue-ice site, however, requires that intense cleanliness be practiced. In essence, preservation of the facility requires minimizing impact to the site.

Operation of aircraft and/or tractors will obvi-

ously introduce pollutants to the continent. Intelligent preparation of equipment prior to fielding and adoption and enforcement of procedures to minimize negative effects of the operation of these vehicles in Antarctica is recommended.

A rigorous analysis to identify the expected level of environmental impact should be planned and initiated once a delivery option is identified as likely to proceed to development. Such an assessment was begun in 1991 for inland blue-ice sites.

HARDWARE AND COST ANALYSIS

Clearly many issues are associated with analyzing the various delivery options identified here. Managers of the Antarctic Program and those assigned to participate in decision-making for the new South Pole Station will have to define their needs, identify resource constraints, and then assess delivery options in light of the entire program. We are not currently in a position to make a recommendation to the U.S. Antarctic Program, but we can offer comments and analysis on the logistical and "mechanical" aspects of these delivery options.

Based on the assumptions made for the tracked trailers and sleds, we favor trailers for either the traverse (86,200- vs. 80,000-lb payload) or the air-to-traverse (14 vs. 12 pallet positions) option. Tracked trailers display a narrower range of towing resistance with varying terrain (compared with sleds), and they are more controllable during towing on slopes with very low friction coefficients. These features of tracked trailers make it possible to sustain a more uniform traverse speed over the entire route. Tracked trailers are somewhat more complex than sleds, however, and maintenance issues and initial cost may need to be considered as well. Our analysis and calculations assume the use of tracked trailers.

Table 2 lists our estimates of the hardware, fuel, hours, and other factors needed for each option to move cargo to the South Pole over a four- or eight-season period. Table 3 converts the information in Table 2 into costs. (A brief explanation of how the values in Table 3 were derived is given in Appendix A.) Since many of the values used to develop these tables are subject to change, they were produced on a spread sheet for ease of recalculation. The results of calculation for numbers of planes and tractors needed each season was often fractional. Taking into account the inevitable downtime with either planes or tractors, and allowing for reserve equipment so that operations can continue while routine maintenance is being performed, we have listed the num-

Table 2. Parameters used for comparison of option costs.

Option Feasibility Delivery period (yr)		Direct air Unknown		Via Mt. Howe Feasible		Via Mill Glacier Feasible		Tractor McMurdo- South Pole Unlikely		Tractor 67°S- South Pole Possible	
		4	8	4	8	4	8	4	8	4	8
Air distance	nm	728	728	630	630	440	440				
C-130 speed	kt	250	250	250	250	250	250				
Air season	days	32	32	32	32	32	32				
Flying time	hr/day	12	12	12	12	12	12				
Total payload*	Klb	13,496	18,992	13,831	19,438	14,054	18,992				
Total round trips required		45	633	461	648	468	633				
Single flight time	hr	5.82	5.82	5.04	5.04	3.52	3.52				
Total flight time	hr	2,620	3,688	2,324	3,264	1,648	2,232				
Flight hours/season	hr	655	461	581	408	412	279				
Flight days required/season	days	55	38	48	34	34	23				
Planes required/season		1.71	1.20	1.51	1.06	1.07	0.73				
Planned planes/season		2	1.5	2	1.5	1.5	1				
Tractor distance	mi			352	352	660	660	2,376	2,376	3,036	3,036
Effective tractor speed	mph			6.5	6.5	6.5	6.5	4	4	4	4
Single trip time	days			3.26	3.26	5.23	5.23	25.75	25.75	32.63	32.63
Tractor season	days			60	60	60	60	80	80	80	80
Trips/season/tractor				15	15	10	10	3	3	2	2
Weight of fuel/trip/tractor	lb			1,860	1,860	3,488	3,488	12,556	12,556	16,044	16,044
Delivered load/trip	lb			84,362	84,362	82,734	82,734	73,666	73,666	70,178	70,178
Del load/tractor/season	lb			1,265,427	1,265,427	827,342	827,342	220,997	220,997	140,356	140,356
Required load/season	lb			3,374,000	2,374,000	3,374,000	2,374,000	3,374,000	2,374,000	3,374,000	2,374,000
Min tractors required/season				2.67	1.88	4.08	2.87	15.27	10.74	24.04	16.91
Planned tractors req/season				4	3	6	5	18	14	30	20
Planned trailers req/season				8	6	12	10	36	28	60	40
Construction material	8,000,000 lb										
Fuel for South Pole/yr	1,374,000 lb										
Fuel weight/gal	6.87 lb										
Maximum payload/tractor	122,222 lb										
Maximum payload/flight	30,000 lb										
Single trailer weight	18,000 lb										
Tractor fuel consumption	1.3 nm/gal										

*Includes cargo of construction materials and fuel for South Pole and for tractors.

Table 3. Cost comparison of various delivery options (values in thousands of dollars).

Option Feasibility Delivery period (yr)	Direct air Unknown		Via Mt. Howe Feasible		Via Mill Glacier Feasible		Tractor McMurdo- South Pole Unlikely		Tractor 67°S- South Pole Possible	
	4	8	4	8	4	8	4	8	4	8
1. Research/feasibility demo	792	792	261	261	150	150	1,349	1,349	1,600	1,600
2. Infrastructure										
a. Initial cost	75	75	300	300	275	275	75	75	500	500
b. Maintenance	0	0	60	120	60	120	20	40	100	200
c. Delivery	97	97	141	141	69	69	97	97	0	0
3. Mobile equipment										
a. Initial cost	960	960	2,175	1,775	2,975	2,575	7,900	6,300	13,000	9,000
b. Delivery	130	130	281	281	196	196	0	0	0	0
c. Maintenance	80	160	112	184	152	264	420	600	700	1,000
d. Fuel	13	27	34	47	62	86	238	334	318	446
e. Operators	58	115	313	440	512	720	2,388	3,361	3,176	4,470
4. Personnel for load/unload										
a. Salary	192	384	288	576	288	576	288	576	288	576
b. Placement	0	0	56	112	39	79	0	0	15	30
c. Subsistence	0	0	19	38	19	38	0	0	29	58
5. Flights										
a. Placement	1,116	2,231	1,116	2,231	1,116	1,116	0	0	0	0
b. Operation	7,307	10,283	6,480	9,108	4,599	6,215	0	0	0	0
c. Sea delivery	0	0	0	0	0	0	0	0	5,400	10,800
Total cost	10,820	15,254	11,636	15,614	10,512	12,479	12,775	12,732	25,126	28,680
Cost ratio	1.03	1.45	1.11	1.49	1.00	1.19	1.22	1.21	2.39	2.73
Labor rate (\$/hr)										
Fuel cost (\$/gal)										
C-130 cost (\$/hr)										

ber of vehicles that should be available for each option. While fractional numbers are unrealistic in the case of tractors, a requirement for one and one-half planes could mean that one plane is dedicated to transport for the entire season and a second plane is only required for half of the season. In terms of aircraft placement cost, however, calculations were based on rounding fractional values to the next higher whole number.

DISCUSSION

Table 2 indicates, as one might intuitively guess, that delivery via direct air with wheeled aircraft is the simplest way to deliver cargo to the South Pole. However, we don't know at this time if this option is possible. A snow runway compacted sufficiently to carry wheeled C-130s has never been constructed with very cold snow as is present at the South Pole. Until recently most people thought that it would be impossible to do so. A successful feasibility demonstration will be required before getting very serious about this option.

Based on our estimates of cost (Table 3), the most economical means of delivering supplies to the South Pole over a four-year period is via the Mill Glacier blue-ice runway. The lowest cost eight-year option involves traversing either from McMurdo or via Mt. Howe. However, considering the fact that many of the values used to derive this comparison are estimates, it is probably most beneficial to compare the options by a cost ratio. This is included in Table 3 using the Mill Glacier four-year option as a baseline; all options have a cost ratio that is some multiple of this lowest cost option. Comparison of the cost of each option is shown graphically in Figure 9.

The delivery scenarios that we evaluated range from 1.03 to 2.73 times the cost of the scheme where materials are delivered via Mill Glacier over a four-year period. Reviewing the cost ratios, it is interesting to note that a four-year delivery schedule is cheaper than an eight-year scenario when aircraft are involved. This is the result of the cost of placement of aircraft and the fact that the Program is only charged for actual flight hours, allowing them to take advantage of fractional numbers of required airplanes. In general, it should be more economical to spread the delivery period over eight years when only tractor-trailers are involved. This is due to the lower number of tractors required when spreading out the delivery period and the fact that a tractor-trailer system represents a sunk cost. However, the additional cost of operators and, in the case of using a coastal station, the doubled cost of ship delivery for the eight-year scenario, overshadow the gains made by reducing the number of tractor-trailers required. It could be possible to operate the ship only every other year to a coastal station if the station could stockpile materials over winter. This would significantly reduce the cost of this option.

It should be kept in mind that an extra four years of fuel for South Pole Station are included in all of the eight-year delivery schemes, making direct comparison of the four-year and eight-year options not entirely fair.

These comparisons were made with aircraft support provided by C-130s only. If larger or more economical aircraft could be used at either the blue-ice sites or the South Pole, it would be necessary to recompute estimated costs for each delivery option.

Another economic factor that is not considered in Table 3 is the residual value of purchased hardware. The tractors, trailers, and infrastructure (includ-

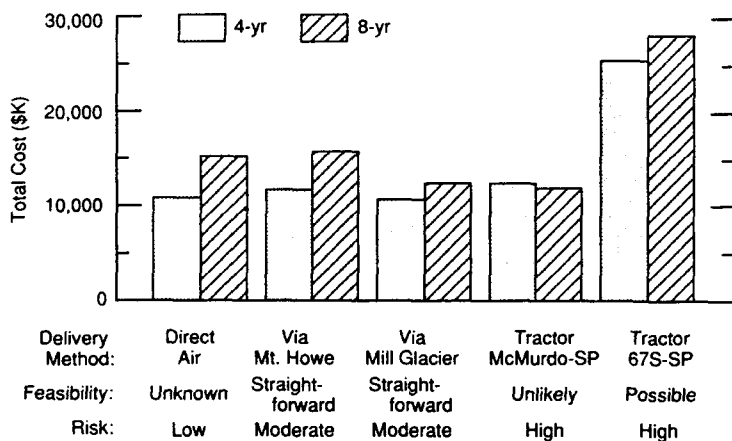


Figure 9. Comparison of delivery schemes.

ing runways) at inland or coastal sites may in many cases have continued value after the new South Pole Station is completed. For instance, it may be desirable to continue to deliver all of South Pole Station's fuel via the selected delivery option. Further, with minimal modification, the tractor-trailer units may be suitable for science traverses in Antarctica.

CONCLUSIONS

Our analysis includes risk, feasibility, and estimated cost for each of five possible options. A decision on which delivery scheme is "best" based on any one of these issues alone would be very misleading. Unfortunately, gaps in our knowledge exist in many areas of this topic. It appears to us that not enough is yet known to provide a clear indication of which delivery scheme is most favorable.

Clearly, a delivery scheme must prove to be feasible. Taking this as a first step, it would seem that either using an inland blue-ice and overland traverse scheme or traversing from a coastal station are the most likely options to consider at this time. Additional studies (including field work) are necessary to determine if overland traverse from McMurdo or direct wheeled landings at the South Pole are eligible for consideration.

Up to a point, we consider cost to be the next sorting factor. Since our cost calculations require the assumption of many values, we would caution against using them for anything more than gross relative estimates of cost at this time. Based on the two schemes considered viable with current knowledge, our cost estimates clearly favor (by a factor of two) using an inland blue-ice site over traversing from a coastal station. The cost differential between the Mt. Howe and Mill Glacier options is insignificant within the scale of this study and should not be considered real without further refinement.

The risk factor also favors inland blue-ice station use over overland traverse as well. We see no difference in the risk associated with either Mt. Howe or Mill Glacier.

There is not a large difference between the cost of delivery over four or eight years when one considers that twice as much fuel is delivered under the eight-year option. Thus, we suggest that other factors be used to determine which time period is favored (e.g., construction schedule, availability of aircraft, personnel required).

Many factors could easily change drastically the conclusions we have outlined here. We consider this

study to be valuable as a starting point for planning and establishing a strategy for certain issues associated with the new South Pole Station. Factors such as maximum desired piece size could easily drive the design of a delivery mode, if that were deemed to be top priority or could be shown to significantly affect other important aspects of construction. Cooperative agreements with other countries or internal agencies (such as NASA) or a need to complete delivery of construction materials within a given time period could also dictate what delivery system must be used. Thus, we feel that this work is best viewed as a framework for in-depth analysis and decision-making about materials delivery to the South Pole. As such, it should be incorporated as part of the broader study to design and construct the new South Pole Station.

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APPENDIX A: DERIVATION OF VALUES IN TABLE 3.

Direct air

1. *Research/feasibility demo*: Estimated cost to develop technology and demonstrate feasibility; includes cost to build one runway and purchase of a processor (blower or power harrow and a prime mover) for \$250K.
2. *Infrastructure*.
 - a. *Initial cost*: Building to house "K"-type loader and other cargo-handling equipment. (Cost to build first runway is included in item 1.)
 - b. *Maintenance*: Maintenance of cargo-handling-equipment building is considered negligible. (Runway maintenance is included in item 3.)
 - c. *Delivery*: Estimate six C-130 flights to deliver building materials for equipment shelter to South Pole Station.
3. *Mobile equipment*.
 - a. *Initial cost*: One "K"-type loader at \$250K, two rollers at \$80K each, one tracked loader at \$200K, and two tractors at \$175K each. (In addition to the processor included in item 1.)
 - b. *Delivery*: Estimate eight C-130 flights to deliver equipment to South Pole Station.
 - c. *Maintenance*: Estimated at \$20K/season for all mobile equipment.
 - d. *Fuel*: Annual work estimated to be four 6-day weeks with two 10-hr shifts and 2 vehicles, which equals 960 hr of operation. Estimate fuel usage at 5 gal/hr and \$0.70/gal.
 - e. *Operators*: Assume labor rate of \$15/hr for 960 hr each season.
4. *Personnel*.
 - a. *Salary*: Estimate 4-person crew at both McMurdo and South Pole working 40-day wheeled season for 10 hr/day at \$15/hr.
 - b. *Placement*: No extra cost.
 - c. *Subsistence*: Extra cost is considered negligible.
5. *Flights*.
 - a. *Placement*: Placement paid for two C-130 aircraft for both the 4-yr and 8-yr options. Placement is calculated as 50 hr of flight time/plane/season.
 - b. *Operation*: Total flight hours \times hourly flight cost of \$2789.
6. *Sea delivery*: Assume no extra cost to program for delivery by annual McMurdo resupply vessel.

Via Mt. Howe

1. *Research/feasibility demo*: Estimated cost to analyze and mark site, demonstrate feasibility of flights,

and establish overland traverse to South Pole Station.

2. *Infrastructure*.
 - a. *Initial cost*: Estimate for buildings needed at Mt. Howe.
 - b. *Maintenance*: Annual heating and maintenance costs for buildings at Mt. Howe estimated at \$15K.
 - c. *Delivery*: Estimate eight C-130 flights to deliver buildings.
3. *Mobile equipment*.
 - a. *Initial cost*: Four tractors and 8 tracked trailers (4-yr option) or 3 tractors and 6 tracked trailers (8-yr option) at \$400K/system, 2 wheeled loaders at \$150K each, 1 "K"-type loader at \$250K, and 1 utility vehicle at \$250K.
 - b. *Delivery*: Estimate 20 C-130 flights to deliver equipment.
 - c. *Maintenance*: Estimate each tractor-trailer system costs \$5K/yr to maintain and all other vehicles cost a total of \$8K/yr.
 - d. *Fuel*: Total fuel usage for tractors \times \$0.70/gal + estimated fuel used by load/unload operations (\$4K).
 - e. *Operators*: Total number of operating hours \times two operators/tractor \times \$15/hr.
4. *Personnel*.
 - a. *Salary*: Assume 4-person teams at South Pole, Mt. Howe, and McMurdo operating for 40 days/season, 10 hr/day \times \$15/hr.
 - b. *Placement*: The only extra cost is one C-130 flight to Mt. Howe each operating season.
 - c. *Subsistence*: The only extra cost is for a 4-member party at Mt. Howe for 40 days/season; assume \$30/day for subsistence.
5. *Flights*.
 - a. *Placement*: Placement needed for two airplanes for each option; estimated 50-hr placement flight each season.
 - b. *Operation*: Total flight time \times hourly cost for plane of \$2789.
6. *Sea delivery*: No extra cost for supplies arriving on annual McMurdo resupply ship.

Via Mill Glacier

1. *Research/feasibility demo*: Estimated cost to ready site for regular air traffic and develop overland traverse route to South Pole Station.
2. *Infrastructure*
 - a. *Initial cost*: Estimate for buildings needed at Mill Glacier, taking into account that one building already exists at the site.

- b. *Maintenance*: Annual heating and maintenance cost for buildings at Mill Glacier estimated at \$15K.
- c. *Delivery*: Estimate seven C-130 flights to deliver buildings.
- 3. *Mobile equipment*.
 - a. *Initial cost*: Six tractors and 12 tracked trailers (4-yr option) or 5 tractors and 10 tracked trailers (8-yr option) at \$400K/system, 2 wheeled loaders at \$150K each, one "K"-type loader at \$250K, and 1 utility vehicle at \$25K.
 - b. *Delivery*: Estimate 20 C-130 flights to deliver equipment.
 - c. *Maintenance*: Estimate each tractor-trailer system costs \$5K/yr to maintain and all other vehicles cost a total of \$8K/yr.
 - d. *Fuel*: Total fuel usage for tractors \times \$0.70/gal + estimated fuel used by load/unload operations (\$4K).
 - e. *Operators*: Total number of operating hours \times 2 operators/tractor \times \$15/hr.
- 4. *Personnel*.
 - a. *Salary*: Assume 4-person teams at South Pole, Mill Glacier, and McMurdo operating for 40 days/season, 10 hr/day at \$15/hr.
 - b. *Placement*: Only extra cost is one C-130 flight to Mill Glacier for each operating season.
 - c. *Subsistence*: Only extra cost is for 4-member party at Mill Glacier for 40 days/season; assume \$30/day for subsistence.
- 5. *Flights*.
 - a. *Placement*: Placement charged for 2 planes for 4-yr option and one plane for 8-yr option; estimated 50-hr placement flight each season.
 - b. *Operation*: Total flight time \times hourly cost for plane of \$2789.
- 6. *Sea delivery*: No extra cost for supplies arriving on annual McMurdo resupply ship.

Over-snow from McMurdo

- 1. *Research/feasibility demo*: Estimated cost to map, mark, and pioneer traverse route to demonstrate feasibility. Includes the purchase of 2 tractor-trailer systems.
- 2. *Infrastructure*.
 - a. *Initial cost*: Building to house "K"-type loader and other cargo-handling equipment at South Pole.
 - b. *Maintenance*: Estimate \$5K/season to maintain cargo-handling-equipment building.

- c. *Delivery*: Estimate six C-130 flights to deliver building materials for runway facilities.
- 3. *Mobile equipment*.
 - a. *Initial cost*: Sixteen tractors and 32 tracked trailers (4-yr option) or 12 tractors and 24 tracked trailers (8-yr option) at \$400K/system, 4 loaders (2 at \$150K each and 2 at \$200K each). (In addition to the 2 tractor-trailer systems included in item 1.)
 - b. *Delivery*: Ship delivery to McMurdo is covered in item 6.
 - c. *Maintenance*: Estimate \$5K/yr for each tractor-trailer system, and a total of \$15K/yr for all other vehicles.
 - d. *Fuel*: Total fuel usage for tractors \times \$0.70/gal + estimated fuel used by load/unload operations (\$2K).
 - e. *Operators*: Total number of operating hours \times 2 operators/tractor + 1 mechanic for each 4 tractors \times \$15/hr.
- 4. *Personnel*.
 - a. *Salary*: Assume 4-person teams at South Pole and McMurdo operating for 60 days/season, 10 hr/day at \$15/hr.
 - b. *Placement*: No extra cost.
 - c. *Subsistence*: No extra cost.
- 5. *Flights*. None.
- 6. *Sea delivery*: No extra cost for supplies arriving on annual McMurdo resupply ship.

Over-snow from coastal station

- 1. *Research/feasibility demo*: Estimated to be slightly more than development of the McMurdo-South Pole overland option. Development cost includes the purchase of 2 tractor-trailer systems at \$400K each and 2 wheeled loaders at \$150K each.
- 2. *Infrastructure*.
 - a. *Initial cost*: New construction or upgrade of existing facilities (estimated) at a coastal location.
 - b. *Maintenance*: Maintenance of facilities estimated at \$25K/yr.
 - c. *Delivery*: Assume sea delivery of materials to coastal station (see item 6).
- 3. *Mobile equipment*.
 - a. *Initial cost*: Twenty-eight tractors and 56 tracked trailers (4-yr option) or 18 tractors and 36 tracked trailers (8-yr option) at \$400K/system, 2 wheeled loaders at \$150K each, and 2 tracked loaders at \$200K each. (In addition to the 2 tractor-trailer systems and 2 loaders included in item 1.)

- b. *Delivery*: Ship delivery to coastal station (see item 6).
 - c. *Maintenance*: Estimate each tractor-trailer system costs \$5K/yr to maintain and all other vehicles cost a total of \$25K/yr.
 - d. *Fuel*: Total fuel usage for tractors \times \$0.70/gal + estimated fuel used by load/unload operations (\$3K).
 - e. *Operators*: Total number of operating hours \times 2 operators/tractor + 1 mechanic for each 4 tractors \times \$15/hr.
- 4. *Personnel*.
 - a. *Salary*: Assume 4-person teams at coastal station and McMurdo operating for 60 days/season, 10 hr/day at \$15/hr.
 - b. *Placement*: Estimated.
 - c. *Subsistence*: At the coastal station assume 4 persons for 60 days at \$30/day.
 - 5. *Flights*: None.
 - 6. *Sea delivery*. Assume annual vessel cost is \$30,000/day and a 45-day round-trip from Pt. Hueneme to the coastal station.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestion for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE July 1993		3. REPORT TYPE AND DATES COVERED	
4. TITLE AND SUBTITLE Delivery of Fuel and Construction Materials to South Pole Station				5. FUNDING NUMBERS Contract OPP-91-40015	
6. AUTHORS Stephen L. DenHartog and George L. Blaisdell					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Cold Regions Research and Engineering Laboratory 72 Lyme Road Hanover, New Hampshire 03755-1290				8. PERFORMING ORGANIZATION REPORT NUMBER Special Report 93-19	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Division of Polar Programs National Science Foundation 1800 G. Street Washington, D.C. 20550				10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. Available from NTIS, Springfield, Virginia 22161				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) <p>Plans are underway to rebuild South Pole Station, ideally with minimal impact on the current science and operational program. The new station will require the delivery of massive amounts of construction materials to this remote site. The existing means of delivering material and fuel to the South Pole include the use of specialized and rare LC-130 Hercules aircraft that can operate on wheels or skis, and some materials are also air-dropped from C-141 aircraft. Neither of these delivery systems is expected to be capable, within a reasonable time period, of supporting both current operations and the transport needs for construction of a new station. Several options for moving construction materials and fuel to South Pole Station are analyzed. All of our options assume that goods will be transported to the Antarctic continent by ship. The options include a) construction of a snow runway at the South Pole capable of supporting wheeled aircraft, b) development of an inland blue-ice runway capable of supporting heavy wheeled aircraft, located as close as possible to the South Pole, with over-snow vehicle haulage from the runway to the Pole (two potential sites are considered), c) over-snow vehicle haulage from McMurdo across the Ross Ice Shelf, up the Skelton or another glacier, and over the polar plateau to the Pole, and d) vehicle haulage from some coastal station (located at about 67°S latitude) with an easier access route onto the polar plateau. Pros and cons of these options are discussed and issues associated with each are identified. The feasibility and risk associated with each option are covered as well. Estimates of costs for many of the factors involved with each option allow financial comparison of each delivery scheme. Ultimately, the results of this study are probably best used as a starting point for any serious planning and budgeting for the development of a new South Pole Station.</p>					
14. SUBJECT TERMS Antarctica Ice runways Logistics Mobility Snow runways Traverses				15. NUMBER OF PAGES 25	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED		18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED		19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	
20. LIMITATION OF ABSTRACT UL					