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Design and Operational Issues While Tunneling in Firn at the South Pole Station

Michael Walsh

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Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755

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ABSTRACT

Locating utilities on the surface at the United States' Amundsen-Scott South Pole Station causes many maintenance problems unique to that environment. The extreme low temperatures, drifting snow, and long, dark winters all restrict easy access to these critical components for most of the year. To avoid these problems, a tunneling system to drive tunnels in the dense, hard firn at the South Pole was designed and built for the National Science Foundation, Office of Polar Programs. From 1996 through 2002, a series of 2 ¥ 3-m tunnels were driven for the water system for both the current station and the new station at the pole. This report describes the design and operational problems that were addressed while driving these tunnels at Pole.

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PREFACE

This report was prepared by Michael R. Walsh, Mechanical Engineer, Engineering Resources Branch, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center, Hanover, New Hampshire. Funding for the project was provided by the National Science Foundation, Office of Polar Programs, Frank Brier, Facilities Engineer, U.S. Antarctic Program.

The design and testing phases of the project were led by Donald Garfield, former Chief, Engineering and Measurement Services Branch, CRREL. John H. Wright, Raytheon Polar Services Co., led the tunneling program for the major series of tunnels during the 1999 through 2001 seasons and provided most of the information on system performance during that phase of the program.

Technical review of this report was provided by Dr. James Lever, Research Mechanical Engineer, and Dr. Jon Zufelt, Research Civil Engineer, both of CRREL. Further review was provided by Thomas T. Tantillo, Chief, Engineering Resources Branch, CRREL; Mark J. Hardenberg, Publishing and Technology Transfer Branch, Information Technology Laboratory, was the editor.

The Commander and Executive Director of the Engineer Research and Development Center is Colonel James R. Rowan, EN. The Director is Dr. James R. Houston..

Design and Operational Issues While Tunneling in Firn at the South Pole Station

MICHAEL WALSH

1 INTRODUCTION

The South Pole Tunneling System was designed and built at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, N.H., to fulfill a requirement of the National Science Foundation (NSF) to develop tunnels at the Amundsen-Scott South Pole Station (Walsh 1999). The tunnels are to be used for personnel access and the housing of utilities for sites near the station. The original mission for the system was to machine a 1-km tunnel between the current (1992) South Pole Station and the new atmospheric research station, located grid west* of the main station. As the project progressed, the mission evolved into the creation of utilidors to support the new main station under construction at that time.

The tunneling system can trace its ancestry back to the late 1950s. From about 1957 to 1964, the U.S. military experimented with several concepts for tunneling in snow and ice. In the early years, coal mining equipment was used or modified to drive tunnels in Greenland. These systems were unreliable, required a large contingent to operate and support, and were expensive. In the early 1960s, a tunneling machine specifically designed for snow and ice was built by a New England mining equipment manufacturer under contract to CRREL. This machine, known as the Russell Miner, was a horizontal roadheader-type tunneling machine that employed a pneumatic debris transport system. After several years of development work, the Army abandoned this project because of operational difficulties, specifically, problems with the debris transport system.

In 1992, CRREL was funded by NSF to investigate design concepts for a tunnel at the South Pole. Design of a tunneling system started in mid-1992, based on the results of investigations conducted at the South Pole (Sodhi et al. 1993). Tests scheduled for Greenland in late 1992 were cancelled for budgetary reasons and because of the status of the system at that time. Testing in northern Maine in early 1993 was cancelled due to a lack of snow, with testing moved to a local ski area where a mound of snow was manufactured for our tests. This snow mound

* Cardinal directions at the South Pole are set up on a grid system, with the direction from the pole to Greenwich, England (prime meridian) being grid north.

was not made correctly, and combined with the relatively high (–20°C) temperatures, testing was of limited value. However, modifications were made to the equipment that were critical to its later performance. The equipment was completed and shipped out for Antarctica in August 1993 for deployment in November of that year. Budgetary constraints in the Antarctic program resulted in the postponement of the deployment to the south pole until January 1996. The equipment was stored at McMurdo Station in Antarctica until that time.

2 DEPLOYMENTS

A total of seven deployments occurred over the course of the project. Of these, four were primarily tunneling deployments, two were system tests, and one was for equipment modification (Table 1). Of the four tunneling deployments, the first (1996–97) was a proof-of-concept mission to determine if tunneling was feasible with the newly developed system.

Table 1. Antarctic field deployments for tunneling project.

Year	Mission	Location	Participants
1995–1996	System testing	South Pole	CRREL
1996–1997	Proof-of-concept tunnel	South Pole	CRREL
1997–1998	Equipment modifications	McMurdo Station	CRREL
1998–1999	Equipment modifications, testing, and training	McMurdo Station South Pole	CRREL / ASA
1999–2000	Main tunnel—1	South Pole	ASA / CRREL
2000–2001	Main tunnel—2	South Pole	RPSC / CRREL
2001–2002	Branch tunnels	South Pole	RPSC / CRREL

Deployments occurred during the austral summer when light and temperature conditions permit flights to the South Pole. The window available for operations is from early November to the end of January, a short period in which to conduct an operation as complex as driving a tunnel.

The first three deployments involved the design team from CRREL. The objectives were to reassemble the system at the South Pole following transport from the U.S., test it in cold weather at the Pole, and install a working proof-of-concept tunnel to service the current station. After the initial tunnel was completed, the system was subjected to an engineering analysis to address some of the shortcomings that became apparent. Logistical difficulties prevented the results of the analysis from being applied completely to modify the tunneler during the third deployment to Antarctica.

For the fourth deployment, the major system modifications were completed, and the tunneler was turned over to NSF and their site contractor, Antarctic Support Associates (ASA). CRREL was joined at that time by John Wright of

ASA at McMurdo Station and John Penny of ASA at the Pole. After the system's modifications were completed at McMurdo, it was flown to the Pole, where it was tested. A symbolic turning over of the keys following testing marked the transfer of the equipment to the contractor.

The last three deployments represented the major thrust of the project. A crew of professional miners and tunnelers completed the main tunnel and a series of davits that will be used to support the new station, which was under construction at that time. Engineering support was provided via the Internet by CRREL from Hanover, New Hampshire. The system evolved over the course of the three seasons.

3 SITE CONDITIONS

The South Pole Station (Fig. 1) is located at the geographic South Pole on the Antarctic icecap. During the project period, it was accessible only by air from McMurdo Station on the Ross Ice Shelf. Repair facilities were extremely limited on site. The nearest source for equipment and supplies is New Zealand, far to the north.

The site conditions at the South Pole made this project unique. The average annual temperature is –54°C. The elevation at the pole is 2900 m. However, the centrifugal force of the earth's rotation on the atmosphere causes bulging of the atmosphere at the equator and thinning at the poles, resulting in a physiological elevation of 3300 to 4300 m.

The working parameters given for the tunnel design were an in-tunnel temperature of –54°C, surface temperatures averaging around –30°C, and an average wind speed of 5.5 m/s. The material to be machined in the process of driving the tunnels at pole is a form of snow known as firn, a strong, dense multi-year type of snow that occurs at depths of 0.5 to 10 m below the surface at the pole. The density of the firn at the 9-m design depth was given as 500 kg/m^3 with a strength of 0.5 MPa. While there is continuous daylight on the surface during deployment periods, no visible light can penetrate to the design depth of the tunnel.

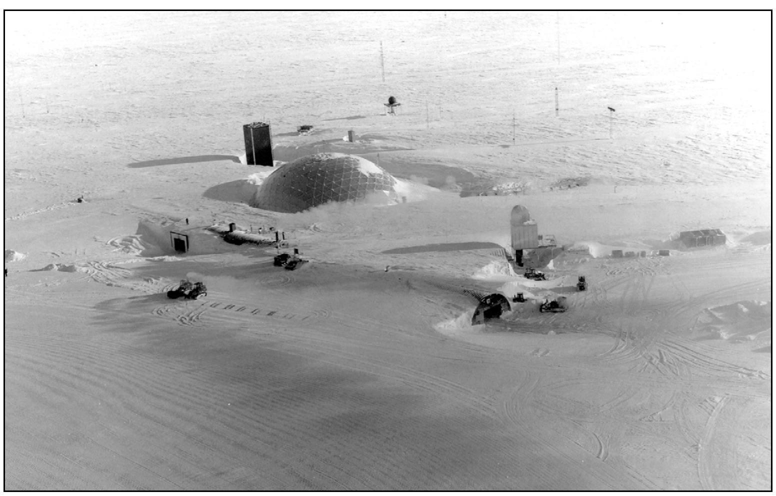

Figure 1. South Pole Station.

4 SYSTEM OVERVIEW

The design and layout of the tunneling system is described in Walsh (1999). A brief description of the system will be given here to familiarize the reader. The original system has been modified in details but the basic structure remains as designed in 1991. The description here will be of the system as modified in 1999. There were no major modifications after that date.

The South Pole Tunneling System is designed to be self-supporting. The basic layout is given in Figure 2. The tunneler is based on a small diesel-hydraulic tracked excavator, modified to run on electric power when underground. The debris disposal system is powered by a surface-based centrifugal fan. Power for all components is provided by a diesel-powered generator set in the generator module. A workshop is provided for minor repairs, and a small warm-up shelter (not shown) is provided for below-surface relief from the cold. A ski-mounted drill rig is used to drill holes for power and discharge line access during tunneling operations and to form the escape risers following completion of tunneling.

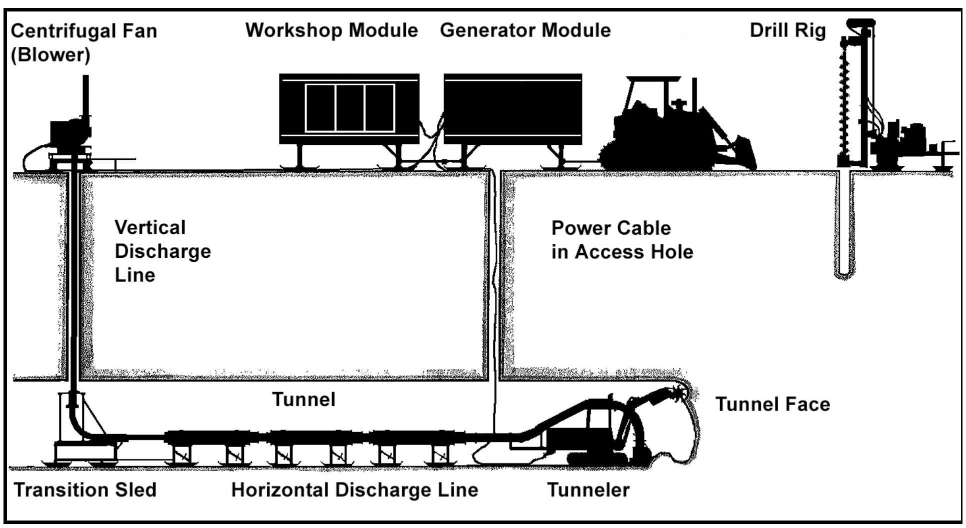

Figure 2. South Pole tunneling system (drawn by Thomas Vaughan).

The tunneling machine is powered by an electro-hydraulic power pack while operating inside the tunnel. A horizontal roadheader-type cutting drum was designed and mounted on the end of the boom of the excavator to machine the face of the tunnel. Chips are gathered at the base of the face by an extensible snowblower, which feeds the debris into the discharge line composed of an ejection tube over the tunneler, a series of telescoping horizontal ducts, through a transition sled, up through a run of vertical ducting to the centrifugal fan. The fan then discharges the debris to the surrounding area. Access holes (30-cm dia.) for power and discharge lines are drilled about every 33 m. Escape risers (1-m dia.) are backbored every 100 m. A set of electronic tilt indicators, supplemented by a laser guidance system, is used to maintain directional control while tunneling.

5 COLD-RELATED ASPECTS

The best design for low temperature conditions is the simplest. This is an adage that can be applied to any design but it is especially important when operating in the –40° range. What is lost in flexibility and sophistication is gained in reliability. At low temperatures, ferrous metals become brittle, fluid viscosities skyrocket, seals and hoses stiffen, and close-tolerance fits gall and seize. The sliding friction of snow turns to that of sand as the coefficient of friction climbs owing to the lack of a liquid contact layer. Murphy loves the cold.

The low temperatures expected drove much of the equipment design. Soft starters were used to reduce the impact of cold starts on the hydraulic system and centrifugal fan. Aluminum and other non-ferrous metals were used whenever possible to avoid brittle failure. Low temperature elastomers were used in seals, power cord insulation, and hoses where possible to reduce stiffness and increase reliability. High viscosity index lubricating fluids were used to allow both startup and operating viscosities within the range of the components. The cutter drum and debris transport system were designed to add as little energy to the cuttings as practical to avoid melting and the subsequent freeze-up of the cuttings in the transport line.

Cold can also be used as an ally. The low ambient temperature of the tunnel can be used to shed waste heat from the hydraulic system. It is also a factor when sizing electrical power cord. The reduced resistance of the line lowers the voltage drop over a given length, allowing the use of a smaller diameter, lighter cord.

6 DESIGN PROBLEMS

The South Pole is a daunting location to test a complex system. The tunneler was originally designed with flexibility in mind as it is an experimental prototype (Walsh 1999). Testing in New Hampshire was of limited value, but enough work was done in the few days of relatively cold weather available to allow some simplification of the design. Flexibility in the drum drive remained necessary to tune the drum characteristics to the actual snow conditions at the South Pole. Testing in the CRREL Materiel Evaluation Facility at –50°C indicated that startup of the tunneler was likely to be a problem if the equipment was cold soaked. Precautions would need to be taken to avoid failure of the hydraulic system. Most of the subsequent problems in Antarctica were with the tunneler, the most complex of the system components (Fig. 3).

Figure 3. Tunneling machine (photo, M.R. Walsh).

The tunneler proved to be underdesigned for the conditions initially encountered at the South Pole. The biggest factor was the higher than expected snow strength attributable to the increased tunneling depth specified upon our arrival. The snow strength that was used in the tunneler design calculations was 0.5 MPa. This was based on an anticipated depth of 9 m and undisturbed snow compacted through natural mechanisms (Gow and Ramseier 1964, Mellor 1964). However, the actual depth of the tunnel was up to 16 m and the area into which the tunnels were driven was highly disturbed and thus more compacted and stronger than anticipated. The difference in strength for these conditions is substantial, over twice that for undisturbed snow. The power required to meet the production goal

(3 m/h) thus went from 8 to about 25 kW. Concurrent with the power, higher torque is necessary to machine the snow and maintain the production rate. The available torque at the drum with the system as originally designed limited the possible depth of cut. In very hard material, approaching the consistency of ice in places (density greater than 800 kg/m^3), the depth of cut was limited to 0.05 m instead of the 0.24 m used under the original design conditions. In 1997, following the analysis of the South Pole tunneling operations in 1996, a 19-kW hydraulic pump was specified to replace the original 10-kW pump. This pump is the maximum size compatible with the original drum drive system. However, a 23-kW pump was shipped by the supplier and installed for testing and training in 1999. This pump was inadvertently left on the unit, overdriving the drum and causing premature failure of the drum drive components in subsequent tunneling operations.

The second critical problem for the tunneler was overheating of the hydraulic system. This was partly ascribable to higher tunnel ambient temperatures than expected, especially in the original tunnel (–37 to –40°C vs. –54°C). The increased ambient temperature resulted in higher than desired system operating temperatures. At –54°C, the heat loss calculations for the tunneler indicated that no heat transfer equipment for the hydraulics would be required at the anticipated power requirements. Both the increased power demands at the drum and the higher ambient temperature in the tunnel led to hydraulic system operating temperatures in the 60 to 80°C range. This resulted in damage to both the oil and the hydraulic components. Some of the damaged components failed and were replaced over the course of operations. The hydraulic system was redesigned in 1998 to help alleviate these problems. These changes are discussed in the *Solutions* section that follows.

The lowered operating temperature of the reconfigured hydraulics reduced the failure rate of components, but failures continued throughout the operations. Valves were the most problematic. Sticking solenoid valves and failed pressure relief valves led to hose failures. The solenoid valve spools would drag and fail to completely open, resulting in the dead-heading of the circuit. Rebuilding the valves with new seal retainers prolonged the life of the valves but did not prevent the problem from recurring. Pressure relief valve failure was caused by sticking relief cartridges and failure of the relief springs. These valves had to be constantly monitored, as malfunction of these valves resulted in ruined pump couplings, snapped pump shafts, and blown hoses. Although low-temperature hose was used (–54°C/20 MPa), the hoses continued to stiffen at low temperatures, making them vulnerable to wear and failure.

The hydraulic fluid used, a low temperature synthetic hydrocarbon oil known as “Oil, Engine, Arctic” (OEA), has a recommended ambient operating range of –54 to 4°C, with maximum allowable sustained operations at 150°C. This oil is classified as 0W-20 or MIL-L-46167. Although it has a pour point of –67°C, start-up viscosity was high enough to promote pump shaft failure (8800 cSt at –40°). This problem was partially solved when more robust pumps were installed on the drum/snowblower circuit in 1999. The high stresses at startup still existed, however, and failure of several coupling spiders can be partially attributed to this.

Some bolts failed because of high stresses on components prone to impact, leading to brittle failure. Use of austenitic stainless steel hardware helped minimize this problem, albeit such bolts have a lower working strength. The use of stainless steel was not always beneficial, though. The original stainless steel drum drive chain had to be replaced due to galling. Some problems occurred in high-vibration joints due to loosening of fasteners that can be partly attributed to differential coefficients of thermal expansion of the two components joined as well as failure of thread locking compounds at low temperature. Some welds failed because of embrittlement along the heat-affected zone. The low temperatures also affected close-fit journal bearings. In several cases, most notably on the pivots of the snowblower frame, these bearings galled, resulting in failure of the mechanism. Impact stress at the drum was a problem in 1996 because of the alignment of the cutters on the drum. Realigning the cutters to allow more even loading of cutting rows of teeth and decreasing the angular offset between the rows significantly reduced this problem.

There are also a few non-site-related design problems with the tunneler. The most significant is the transfer of mining debris from the front of the tunneler to the transport line behind the machine. The design employs a center-impeller two-stage snowblower to center the chips and inject them into the airstream. Because of the necessity of running the debris line over the right side of the tunneler, an angled throat from the impeller scroll to the ejector tube was required (Fig. 4). This is a choke point and is the only location that plugged along the discharge line during tunneling operations. To reduce the instance of plugging, the air was directed through this throat along with the debris. This greatly reduces the frequency of plugging but adversely affects the efficiency of the transport system. To operate effectively as a two-phase stream, the solid debris needs to be injected into an established airflow.

A second problem associated with the center-impeller snowblower is the stress on the joint where the ejector tube meets the snowblower. The ejector tube is unsupported from the snowblower to the end of the tunneler (up to 7 m), with a sliding joint and a large-radius 100° elbow between. When the snowblower is lifted or lowered, extended or retracted, high stresses are experienced at the snowblower joint. In addition, the uneven distribution of weight adds stress to the lift/extension frame for the snowblower. Both assemblies failed several times and were modified. Some problems still persisted, although they may be attributable to overuse of the system.

Figure 4. Front of tunneling machine showing snowblower (photo, M.R. Walsh).

The speed and torque of the snowblower impeller are too low. Because of the configuration of the throat, an attempt was originally made to meter the snow into the airstream through the throat to avoid clogging. This did not prove successful. Higher rotational speed and more torque will be necessary to give the debris enough momentum to fully engage the airstream. This should improve the efficiency of the disposal system.

The excavator upon which the tunneler is based has accumulator-charged spool valve controls. This accumulator failed several times, resulting in sluggish or non-responsive controls. The probable cause for this failure is the extreme low temperatures experienced by the equipment while stored outside over the winter (9 months). The expedient work-around for this problem is to deadhead one of the controls to charge the system up so the remaining controls can be used. This stresses the system, however, and leads to overheating of the oil and hose failure.

The drill rig (Fig. 5) did not operate in the cold as well as expected. Starting the unit was very difficult, even with a block heater and hydraulic oil heater. When back boring the 1-m diameter escape shafts, the drill string tends to whip violently as the bit approaches the surface. This becomes especially dangerous when the bit breaks through. Varying the drilling parameters had little effect on this behavior. A means of stiffening or stabilizing the rod needs to be found and implemented.

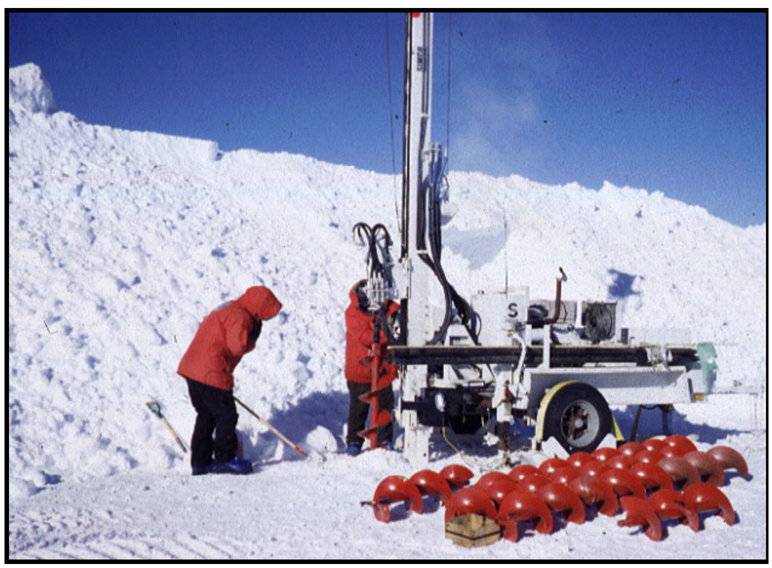

Figure 5. Drill rig used at pole (photo, M.R. Walsh).

Most electronic components held up well, although one digital tilt indicator on the tunneler failed. The battery and charger for the 12-V system on the tunneler failed in the tunnel, resulting in a smoke-in-tunnel incident and evacuation of the tunnel. The soft starter on the centrifugal fan failed once and had to be replaced. The cause of this failure was never identified.

There were a few problems with the spoils transport system. The snowblower at the front of the tunneling machine has already been covered. The expanding ducts and vertical ducts had problems pulling apart during setup and when being moved during operations. This was especially dangerous when installing the vertical ducting as the drop could exceed 15 m when the ducts came apart. A critical problem occurred at the centrifugal fan, where separation of the two-phase flow at the fan inlet led to failure of the electric motor and repeated tripping of the protective breaker.

7 SOLUTIONS

Resolving problems associated with the tunneling system was a difficult task. Logistics to Antarctica are problematic, especially with the concurrent construction of the new South Pole Station. Trips to McMurdo Station in 1998 and 1999 to implement modifications to the system were only partially successful owing to the lack of on-site parts, missing system components lost during shipment from the South Pole Station, and the late or non-arrival of equipment shipped to Antarctica from the United States. The assistance of highly qualified and motivated craftsmen at both McMurdo and South Pole helped to circumvent some of these shortcomings, but the effectiveness of the modifications still suffered as a result. This is a factor that is essentially out of the control of anyone running a project in Antarctica but something that must be expected.

The tunneler will be discussed first. The drum drive problem was caused by a lack of power. The snapped pump shafts experienced during the 1996 deployment were resolved with the installation of the larger pump with a larger input shaft in 1999 (15.87-mm Ø to 31.75-mm Ø input shafts). When the original drum pump was replaced with the more robust unit, it was discovered that the supplier had not shipped the unit specified. The output (with inefficiencies) of the pump supplied was 22.8 kW at 1.32 L/s, 21% higher than the 18.8 kW, 1.1 L/s, unit specified. The pump was slated for replacement prior to the commencement of the 1999–2000 tunneling effort but the task was not carried out. The result was the failure of several hydraulic components, including several drum drive motors. The maximum continuous flow the motor is designed to accommodate is just over 1.02 L/s. The pump was delivering a minimum of approximately 1.3 L/s. The result was overspeeding of the unit and eventual failure. In 2002, the correct pump was installed and hydraulic failures (with the exception of blown hoses) ceased.

Problems still occurred with failed pump couplings, but these were traced to a faulty coupling in one case and misalignment problems owing to an incorrectly machined spacer plate and installation inaccuracies in others.

Overheating of the hydraulics was solved from several fronts. In 1999, all insulation and heat tracing was removed from the hydraulic lines and components, the circuitry was simplified to reduce fitting and component losses, a blower was installed to circulate air around the hydraulic power pack, and the tunneler was run with the side covers removed to enhance heat transfer. This resulted in a 20°C drop in operating temperature for the hydraulics. Not only were line losses reduced but increased air circulation helped cool the system. The blower fan used during the work on the first tunnel in 1996 was not required after the system was modified. Several redundant valves were removed and the return lines enlarged to ease the flow of oil to and from the pumps. Finally, when operations switched to the main tunnel complex in 1999, the ambient operating temperature dropped over 10°C. The only explanation we came up with for this is that the first tunnel was driven in the vicinity of the existing active sewer bulb, a source of considerable heat and some consternation.

The replacement of a stainless steel drive chain on the cutting drum with a special low-temperature case-hardened steel chain eliminated galling failure from lubricant washout. No problems were reported with the steel chain over the course of the following three seasons. Realignment and improved distribution of the cutters on the drum resulted in a more even linear and angular engagement during cutting, greatly reducing feed-in impact and stress on the drum components.

The snowblower frame failures were primarily attributable to tight tolerances on machined parts and stresses from almost constant use. Some of the stress problems were reduced when the frame was redesigned in 1997. The lift cylinder raised the frame in compression rather than in tension as on the original design. Recurrent problems with the frame lift mechanism were traced to two factors: loss of retaining rings on clevis pins and tight pivot bushings. Both these items were addressed successfully in the field.

The ejector tube connection point failure at the snowblower was a recurrent problem that was addressed but never fully resolved. The stresses at that point are quite large, and the joint is stressed often during operation. It was redesigned and rebuilt twice, resulting in increased reliability, but the joint will have to be reexamined if the system is to be used again.

The impeller of the snowblower is located in the center of the unit. To direct the snow to the ejector tube and avoid the boom of the tunneler, a passageway was fabricated from the impeller discharge to the ejector tube. This passage is prone to plugging, and two attempts to widen the passage helped but did not solve the blockage problem. This necessitated the co-location of the inlet for the air with that of the solids on the debris transport system. Although this essentially solved the blockage problem, it reduced the efficiency of the two-phase transport system. This is another area that has been examined and will need to be addressed prior to redeployment of the system.

The problems associated with the remainder of the debris transport system were successfully addressed. Stressing of the horizontal ducting during the frequent positioning of the tunneler were resolved with the fabrication of a short single expansion duct unit that was mounted directly behind the tunneler (Fig. 6).

This unit is much lighter than the regular double expansion units and runs much smoother. The hard stops used on the horizontal ducts to prevent tube separation were removed and expansion limits maintained with cables. This eliminated the pull-out problems experienced earlier when advancing the tunneler. Polyethylene sleeves were inserted in the ducts to facilitate sliding. Hard stops were installed on the opposite ends to limit tube contraction. The separation of the flow at the fan inlet was eliminated by the addition of a 2-m straight expanding duct between the fan and the elbow where the vertical tubing exits the surface (Fig. 7). This had the added benefit of simplifying the positioning of the fan assembly, as its placement at the access hole in the surface was no longer as critical, resulting in reduced setup times.

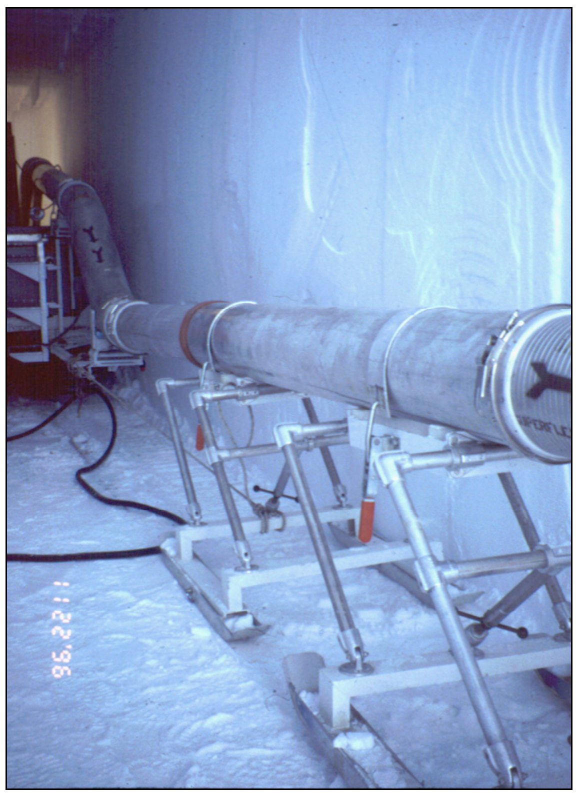

Figure 6. Single-expansion duct unit mounted to tunneler (photo, M.R. Walsh).

The vertical duct line separation was addressed following experience gained in the 1996 deployment. A more robust retention system using circumferential V-clamps was designed for the vertical tubes to prevent tube separation during installation and use. A yoke was designed and the tubes modified to facilitate lowering and raising them in the access hole (Fig. 8). Finally, the retention line for the short sliding tube assembly mounted at the lower end of the vertical tube run was beefed up for better retention of the sliding tube.

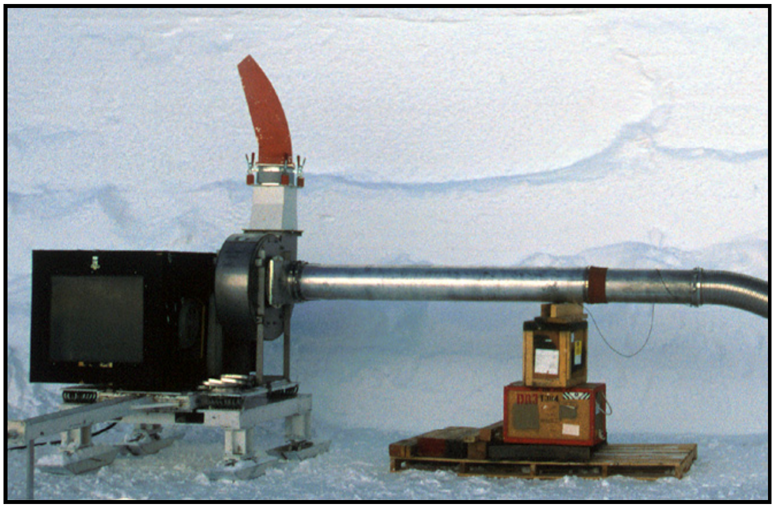

Figure 7. Expandable straight mixing tube at centrifugal fan inlet (photo, M.R. Walsh).

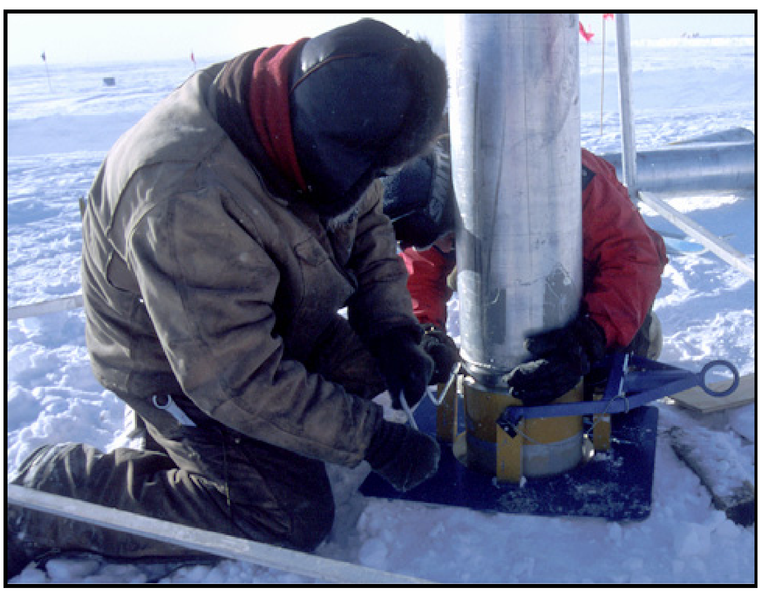

Figure 8. Yoke and attachment arrangement for vertical tubes (photo, M.R. Walsh).

Starting problems with the mobile drill in the cold were resolved by warming the unit for longer periods with a mobile heating unit. This did not fix the problem of cold starting but it was a work-around. The hydraulic reservoir is equipped with heaters, but the oil temperature was too low for efficient operation. Adding an insulated cover to the tank resolved this problem.

Over the course of the several deployments, many of the problems encountered with the design and operation of the system have been solved. This has increased the reliability of the current system to the point that it is comparable to commercial tunnel boring machines. However, the machine is still a prototype with room for improvement.

8 FURTHER WORK

Problems with the hydraulics in general and the drum drive in particular have been examined to a great extent. It is obvious the drum drive was underpowered for the conditions encountered during the tunneling operations. Both a larger hydraulic drive and an electric drive have been considered to power the drum. As the system currently sits, the final chain drive is rated at 16 kW continuous duty. Using a 15% intermittent duty factor, the largest system drive that can be considered is around 18 kW, 23 kW before inefficiencies. Although still undersized (a 23-kW final drive is more suitable), this is a workable system that will not require a major redesign. Going to a larger hydraulic drive system will require the redesign of both the hydraulic and mechanical aspects of the drum drive. An electric drive would weigh in excess of 250 kg and require a major redesign of not only the drive but the supporting mechanism of the drum. The most workable solution for the current system therefore is to reinstall the 23-kW drum drive pump and replace the current drum drive motor with a larger displacement, higher torque model that will directly output the desired speed. Care needs to be exercised prior to cold start to reduce damage attributable to high oil viscosity. Pre-warming the hydraulics with a heater or leaving the hydraulics circulating between shifts will help alleviate the problem.

The solution to the solenoid valve problem for the add-on hydraulics of the tunneling machine is to replace these valves wherever possible with open-center three-way manual diverter valves. These should be used for the drum and snowblower circuits. The manual valves will allow the easing up to speed of the hydraulic motors associated with these circuits, thus eliminating the start-up shock of the electrically actuated solenoid valves as well as the dead-ending problem that occurs when the spools on these valves stick. An additional solenoid valve for the creep feed track circuit can also be eliminated as it is no longer used, thus simplifying the hydraulics further. No replacement valve is necessary for this drive. The pressure relief valves need to be replaced with more robust valves designed specifically for off-road equipment use. Some redundancy may be necessary. The use of these valves, along with upgrading the hydraulic hose to more current low-temperature material and more careful hose assembly fabrication, should reduce the incidence of hose bursting and connector separation on the tunneler. The replacement of some hose assemblies with steel tubing will go even further in this effort.

The snowblower drive is somewhat underpowered and should be driven at a higher speed. Using the next size larger pump will give a 50% increase in speed for the system without affecting the torque. This will accelerate the chips into the airstream at a higher rate and thus should increase the efficiency of the system. Use of an electric motor for this should be considered. This will add about 120 kg to the weight of the system, but this weight can be used to offset the weight of the ejector tube assembly.

The problem with the original excavator controls accumulator is not an easy one to resolve. The accumulator is an integral part of the spool valve assembly, and there is no convenient space to mount a supplemental cylinder-type accumulator, which would be more reliable at low temperatures. The only recommendations that can be made are to ensure the accumulator is discharged whenever the machine is not in use and to preheat the equipment prior to applying pressure during startup.

The debris collection and removal system at the front of the tunneler will need to be redesigned if production rates are to reach those required for more cost-effective use. The impeller needs to be located on the right of the snowblower so that direct injection of the debris into a pre-existing air stream is possible. Reducing the radius of the ejector elbow will reduce the weight of the system and lessen the stresses on the connection at the snowblower. A mid-line support of the ejector tube at the juncture of the sliding tube will further reduce stress on the joint by reducing both the apparent weight and the drag between the tubes during extension and retraction of the snowblower. Finally, better hardware needs to be used to eliminate fastener failure experienced on the current design.

A more effective leveling and steering system must be incorporated into the design. The digital level indicators worked well but were not mounted correctly or in the right places. A better distribution of these sensors will increase the usefulness of the system and make tunneling operations more efficient.

Resolution of the drill string whip problem with the backboring bit may require the fabrication of rod stabilizers for the string. These can be made out of 30-cm pipe cut into shoes attached to the string via a hub and spider. The shoes would ride along the surface of the 30-cm diameter guide hole, thus limiting radial displacement of the string during backboring.

9 ASSESSMENT

The current tunneling system has reached the end of its useful life as a developmental prototype. It has been an extremely valuable tool for learning what is required of a system for tunneling in snow and ice in the extreme cold. The tunneling machine itself needs additional development work before it is sufficiently reliable for use in Antarctica. The remainder of the system components, with minor modifications, are sufficient for what they are designed to accomplish.

Although equipment breakdown problems and delays were maddening at times, the reliability of the system was not very different from commercial equipment. Table 2 illustrates the availability of the equipment over the course of the four seasons it was used. The poor productivity time experienced in the 1999–2000 and 2000–2001 seasons can be attributed primarily to the incorrect drum drive pump. Replacement of the pump in the 2001–2002 season contributed to the highest availability time for that season. Other factors contributed to the 69% availability, such as correcting problems as they developed, but wear and tear offset at least some of these gains. The productive time for commercial equipment is in the 25 to 35% range. The CRREL tunneling system averaged 41%. Our goal with the system was an availability rate of 75%. We approached this at the end of the project, with a 69% availability rate.

Table 2. System statistics over four field seasons.

Season	Total advance (m)	Advance rate (m/hr)	Productive time (%)	Down time (%)	Stand by time (%)	Available time (%)
1996–1997	115	0.9	54	33	13	67
1999–2000	294	0.9	39	51	10	49
2000–2001	287	0.9	35	57	8	43
2001–2002	290	0.8	42	31	27	69

The feasibility of the system cannot be determined at this time. It was only during the last deployment, after the drum pump had been changed out, that the tunneler was operating reliably. The original goal of 3 m/h advance rate was never achieved, initially because of the system being underpowered and problems with phase separation in the debris stream, and later because extra care was being taken with the tunnel alignment and grade. Maximum production rates of about 2 m/h were achieved over short periods but were not sustained. With some modifications to the tunneler, specifically in the snowblower area, the drum power, and a better alignment system, the 3 m/h goal should be achievable, making this method of driving tunnels feasible over medium to long runs (75 m or more).

10 CONCLUSIONS

The CRREL South Pole Tunneling System successfully drove true tunnels in firn at the South Pole. Over the course of four seasons, two tunnel complexes were driven for a total of almost 1 km of 2- × 3-m tunnels. The equipment used to drive these tunnels evolved over the course of the project through redesign, modification, and field repair. The productive rate of the system surpassed the average for commercial tunneling equipment, but production rates never reached the goals set at the start of the project. The debris transport system was the most innovative aspect of the project and worked well after initial modifications. More development work needs to be carried out on the tunneling machine to increase its reliability and power.

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APPENDIX A: TUNNELER DOWNTIME ITEMIZATION

The following table is contained in the tunnel foreman's after-action report from the 1999–2000 season (Wright 2000). It contains a detailed list of all the non-maintenance incidents resulting in work stoppage during that season. The majority of problems occurred with the tunneler hydraulics, specifically the cutting drum drive circuit, although the snow blower frame and hydraulics contributed significantly. Many of the problems that occurred with the other system components during the 1996 deployments were successfully addressed prior to this deployment.

In this and the following tables, *surface fan* refers to the centrifugal fan used to power the debris removal system and *snowblower* refers to the extensible snowblower mounted to the front of the tunneler (Fig. 2).

Table A1. Annotated equipment downtime table.

Date	Problem Area	Comments
Nov 17	Surface Fan	Soft starter broke down Nov 12, repairs/ replacement completed Nov 24
Nov 25	Snowblower	Two hydraulic hose leaks
Nov 25	Duct System	Tinkering with silicone rubber seals to minimize leaking, maximize duct suction, vacuum pressure hose/gage ice plugged
Nov 29	Tunneler Snowblower Tunneler	Repair manual boom lock Re crimp hydraulic hose Re attach breaker box cover
Nov 30	Duct System Duct System Snowblower	Replace silicone rubber seal Replace broken clamp ring flange on blower duct Replace two snap rings and make bushings on lift linkage Repair bad hose crimp, clean up oil spill
Dec 01	Tunneler Snowblower	Fried flex coupling between motor and drum/blower pump, smoke-in-tunnel Re crimp hydraulic hose Left guide slide will not retract, attempt repairs in tunnel, unable to do same, tunneler comes out of hole to shop, redesign, machine, rebuild both guide slides and back in service by Dec 10.
Dec 11	Tunneler	Drum hydraulic motor breaks, locate replacement
Dec 13	Tunneler	Electronic boom inclinometer fries, replace w/ mechanical Drum Hydraulic motor fails again, rebuild same, and install manual bypass valve for motor on boom

Date	Problem Area	Comments
		Battery overcharges, bursts, smoke-in-tunnel, remove battery and charger
Dec 14	Tunneler	Repair 3 hydraulic hose leaks
Dec 15	Tunneler	Repair 2 hydraulic hose leaks
Dec 16	Tunneler	Repair 3 hydraulic hose leaks
Dec 17	Snowblower	Mend tear on transition sled ducting Tighten Allen head bolts on guide slides and extend-cylinder (this becomes a routine exercise twice a shift)
Dec 19	Drill Rig	Drill fails to start after 2 hrs warm up, starts after 3 rd hr., make insulated cover for hydraulic oil tank, works better hence
Dec 21	Snowblower	Pivot pin on lift linkage reinstalled Left guide slide shears off set screws from female Allen bolt receiver, repaired same
Dec 22	Snowblower	General maintenance on extend and lift mechanisms
Dec 23	Snowblower	Replace pivot pins on lift linkage, new pins modified from old ones using tapped holes, bolts and lock washers
Dec 29	Tunneler	Replace burst hydraulic hose
Dec 30	Snowblower	Repair cracks and holes in windshield
Jan 02	Duct System	Replace clamp ring flange on blower duct
Jan 04	Tunneler	Repair hydraulic leak on accumulator manifold, as this is in an awkward location in floor of cab, in-tunnel repair calls for excavation of a mechanic's bay in left rib
Jan 06	Snowblower	Replace split ring on lifting arm Trial test: apply Loc-tite to big Allen bolt on right side guide slide
Jan 07	Snowblower Duct System	Replace windshield strut Replace plywood cover on venturi bell on blower duct
Jan 09	Snowblower	Replace hydraulic hose on ram
Jan 10	Tunneler	Drum motor breaks down, mounting bracket also tears off, rebuilt and replaced Repair two burst hydraulic hoses on drum pressure relief valve, smoke-in-tunnel Drum motor breaks down again, rebuild, replace
Jan 11	Tunneler	Drum motor breaks down again, rebuild, replace, blows seal, replace seal, install seal cover

Date	Problem Area	Comments
Jan 13	Tunneler	Flex coupling torn up and drive shaft on pump (drum and Kubota) severely worn, replaced, required excavating a mechanics bay in right rib and a spill bucket pass in left rib
Jan 14	Tunneler	Modify replacement pump to lower gpm on Kubota as was on original Replace blown hydraulic hose
Jan 15	Tunneler	Drum motor breaks down for the last time, all attempts to resurrect same fail

APPENDIX B: TUNNELER DOWNTIME ITEMIZATION—2000–2001 SEASON

The following table is contained in the tunnel foreman's after-action report from the 2000–2001 season (Wright 2001). It contains a detailed list of all the non-maintenance incidents resulting in work stoppage during that season. Once again the majority of problems occurred with the tunneler hydraulics, specifically the cutting drum drive circuit, while the snow blower frame and hydraulics continued to cause problems. When compared to the problems encountered the previous season (Table A1), many fewer problems occurred over the course of the 2000–2001 season. Table B1 is more detailed under the Problem Area column than Table A1, a reflection of increased familiarity and knowledge of the system.

According to Mr. Wright, there appeared no single "weak link" to the tunneling system. On the contrary, when any single part of the system broke down, all mechanical advance came to a halt. Logistics and procurements shortcomings were as much a contributor to accumulated down time as mechanical breakdown. Table B1 itemizes the failures that contributed to system down time. Note that 1/2 hour to 1 hour per shift was generally logged for routine maintenance.

Table B-1. Annotated equipment downtime table.

Date	Problem Area	Comments
Dec 01–12	Drum motor	Procurement delay, replace
Dec 14	Snowblower motor Generator	Replace, bleed hydraulics Blockage in air intake filter... plastic debris
Dec 15	Drum motor	Mounting bracket
Dec 18	Drum pump	Bleed hydraulics
Dec 19	Drum pump	Replace flex coupling , discover wear on pump shaft
Dec 20	Snowblower guide slides	Hinge pin slips out
Dec 24	Duct system	Repair/replace goose neck flange
Dec 26	Electric motor	Unexplained power off , found machine cold,
Dec 27	Tunneler	Repair 2 hydraulic hose bursts in rat's nest
Dec 30	Drum motor Tunneler	Replace motor, beef up mounting bracket Repair hose burst
Jan 03	Snowblower lift	Lift support weldment broke
Jan 04	Tunneler	Repair 2 hose bursts
Jan 05		In shop for misc. repair after hole through

Date	Problem Area	Comments
Jan 08–16	Drum pump	Procurement delay , Flex couple / pump shaft
Jan 17	Drum pump	Flex couple, replace spider
Jan 19	Tunneler Drum	Repair hose burst Repair cutting drum spoke, and pivot
Jan 20	Tunneler	Repair 2 hose bursts
Jan 21–24	Drum pump	Replace flex couple, pump shaft (wrong size), weld fix flex couple to old worn pump shaft
Jan 29–30	Drum motor	Failure, replacement

Prior to start of tunneling operations the crew performed the following repairs and modifications:

- Re-plumb the drum pump circuit.
- Replace drum pressure relief valve and solenoid valve.
- Reinforce guide slide ends.
- Drain and replace hydraulic oil.
- Re-fabricate pivot pins on snowblower lift linkage.
- Repair snowblower windshield.

APPENDIX C: POST-SEASON ASSESSMENT REPORT FROM CRREL—2000–2001 SEASON

This appendix contains the assessment report filed by the author following the 2000–2001 tunneling season at South Pole (Walsh 2001b). Problems associated with this deployment are discussed and recommendations made based on an assessment of the system failures. Critical in this report is the determination that many of the hydraulic system control problems associated with the drum circuit are attributable to the incorrect pump installed in the system. At that time, the effect on the system requirements due to the increased snow strength at the current tunneling depths had not been examined.

South Pole Tunneling System: 2000–2001 Season

Michael R. Walsh, PE

USA CRREL

16 February 2001

This report summarizes the work done by CRREL in support of the 2000 – 2001 season tunneling effort at the South Pole Station. The author was in contact with the tunneling foreman, Mr. John Wright, throughout the season from arrival at McMurdo Station to demobilization at Pole. The time span covered by this report is 16 November 2000 to 8 February 2001. In addition to communications with Mr. Wright, I also was in contact with Martin Lewis and Michael Papula concerning spare parts for the tunneler over the course of the season.

The changeover from ASA to RPSC did not go well for the tunneling project. Over the course of the summer, the spare parts required for operation of the tunneler did not get ordered, resulting in over a month's delay at the start of the project. Through a coordinated effort on the part of people at RPSC, CRREL, McMurdo, and Pole, the required parts arrived at Pole on 12 December. This allowed some time on site for some badly needed maintenance and repair work to the tunneler, and through e-mail, recommended modifications to the equipment were carried out.

Performance

Tunneling operations began around 14 December. Two significant events occurred over the course of the season. On 4 January, the tunneling crew holed through to the tunnel machined last year. The meeting of the tunnels was spot-on, reflecting the care Mr. Wright has taken in ensuring the correct drift of the tunnels. On 2 February, the main tunnel was completed with the hole-through at the passageway between the two stations. Again, the intersection was spot-on. The tunneling operation ceased activity on 6 February, with Mr. Wright continuing on site for another week to complete the project wrap-up and prepare for next season.

The performance of the tunneling system was similar to that last year, although initial impressions are that the system was somewhat more reliable. The tunneling crew was able to complete as much tunnel as the previous season with one less month of operating time. An assessment of the productivity of the system will need to await the after-action report from Mr. Wright when he returns from Antarctica.

Some of the problems that plagued the tunneling machine last year remained. Primary among these is the continued failure of the drum drive motor. Two motors were lost again this year through the same mechanism: failure of the internal vanes. A coupler between the drum/snowblower tandem pump unit and the main drive motor failed again, resulting in the loss of the splines on the pump input shaft. Burst hoses also caused problems as well as the loss of several pins on the snowblower frame. The frame itself also failed at one point. The last critical problem was the failure of the joint between the front-mounted snowblower and the ejector tube (ducting) that loops over the tunneler. All these problems were overcome through the ingenuity and perseverance of the tunneling foreman and his crew, with an engineering assist from CRREL. I will go into some detail on a few of the problems encountered.

Failure analyses

The failure of the pump coupler was due to a defect on the part. The splines on the pump half of the coupler are supposed to run at least 1.25 in., the length of the splines on the input shaft to the pumps. The coupler on the tunneler that failed had only 0.25 in. of splines. It is amazing that the unit held up as long as it did. No spare parts were available, either for the coupler or the pump. When parts did arrive, **we discovered that the gear pump was the wrong size**, with 1.5-in. wide gears instead of 1.25-in. gears. The foreman had the damaged coupler welded to the ruined shaft and tunneling resumed. Careful alignment of the pump-coupler-drive motor connection reduced cavitation at the pump and resulted in smoother operation of the system.

On 29 January, the drum motor failed for the second time this season. No spare motor was on hand. Although spares arrived and the machine was operational the evening of the 30th, I felt that the problem had to be analyzed more thoroughly to prevent its reoccurrence. Previous work troubleshooting the failure of the drum drive coupling revealed that the oversized pump that was shipped by the distributor had not been replaced with the correct pump from the spare parts list given ASA after the 1999 deployment. The pump currently on board the tunneler has a theoretical output of 21.2 gpm. The drum drive motor has a maximum continuous input capacity of only 16.2 gpm. This likely explains the loss of these drive motors both this season and last. The specified pump for this circuit will deliver a maximum flow of 17 gpm and a probable flow of 15.2 gpm. Sticking control and pressure relief valves also contribute to the downtime associated with this component of the tunneler.

Failure of the snowblower frame was probably due to it wearing out. The frame snapped in half during tunneling operations and was modified and welded in place on the tunneler. I am not sure what part failed, so I can't comment on the mechanism. However, the non-balanced weight of the assembly and the loss of the pins, along with the constant hammering the assembly takes, especially while in transport to and from the heavy shop, must have contributed heavily to the failure.

The failure of the ejector tube joint is due to stress. The ejector tube assembly, over 20 ft in length when fully extended, is supported only at the ends. The snowblower end is at the bottom of an elbow and experiences high lateral as well as vertical forces during lifting and extension of the snowblower. A midpoint support has been sketched up at CRREL to relieve some of the stress but has not been built or implemented.

Discussion

1) *Drum drive*: The drum drive motor needs to be replaced. The current motor is being severely overdriven, leading to frequent and premature failure. There are several options that can be considered. The least obtrusive is to retain the current pump (1.5 in./21 gpm) and replace the drive motor/gearbox with a WSI Model 35S-208-A-12-A. This should be a 1:1 replacement with the existing drum drive unit. The spare drum motor is P/N 35SR-12-A. This will give an output speed of around 113 rpm and an available torque of about 850 ft-lbs.

Preferably, a gerotor-type hydraulic motor will replace the motor/gearbox combination. This reduces the number of components but will require rebuilding the mount at the end of the boom. This may have to be done anyway due to three season's worth of hard use. Two manufacturers were considered based on availability of literature at the time of the analysis. They are White and Eaton, both of whom have excellent reputations in mobile hydraulic equipment. A rotational speed of between 100 and 120 rpm is desired, along with an available torque at the drum of at least 800 ft-lb, with 900 ft-lb or better desirable. A White model DT28 (28.3 cir) will give the same drum performance as the WSI model recommended above. An Eaton Series 10000 Model 119-1029 (29.3 cir) will drive the drum at 109 rpm and 880 ft-lb. The more rugged designs of the gerotor motors allows much higher intermittent operating pressures, so these units may be run at a higher pressure, resulting in higher available torque. A 10% increase in pressure will result in a similar torque increase. Drive sprockets need to be sized to control the drum speed and torque.

2) *Snowblower hydraulics*: Some problems that would have been minor other than at the Pole occurred with the snowblower drive. In one instance, a piece of debris lodged in the pressure relief valve, killing the operating torque of the unit. It was felt by the tunneling foreman that more speed was needed at the snowblower. There are two ways of doing this: with a larger pump or a smaller motor. The larger pump is the easiest way to accomplish this. The current pump is rated at 6 gpm. The next size larger (0.75-in. gears) is rated at 9 gpm. This will increase the impeller/auger speed but not the torque. A 1-in. pump rated at 12 gpm is on site but is not recommended due to inlet velocity cavitation problems experienced at McMurdo. To increase torque, the motor will have to be changed out. A larger capacity motor (6 cir vs. the current 5 cir) will give a 22% increase in torque with a commensurate decrease in speed, but the mounting and shaft dimensions are quite different between these two motors.

3) *Snowblower assembly*: Several problems are inherent in the snowblower assembly. Some of these surfaced during the four tunneling deployments and most have been addressed to varying degrees of satisfaction. There are four major areas of concern that will be discussed here. They are the frame, the impeller location, the intersection of the ejector tube elbow with the snowblower, and the support of the nested ejector tubes adjacent to the tunneler cab.

The frame is a highly stressed component of the snowblower assembly. It was redesigned after the many problems encountered during the two deployments in 1996. Although much more rugged than the original design, high, uneven loads continue to cause sporadic failures. The loss of pins that were retained with clips is being addressed by replacing the pins with more reliable hardware. The one significant failure of the frame was addressed on-site by John Wright and his crew. The frame at this point is too long and needs to be shortened by 6 to 12 in. This will reduce the overhanging load and thus the stresses on the lifting points. Short of returning the tunneler to McMurdo or, better, CRREL, we will have to live with what we have.

The impeller location is a definite impediment to the performance of the tunneler. A commercial center-impeller snowblower was used at the time of the original construction as this was the most expeditious design we could come up with in the short period allowed. What is needed is to modify the current unit to place the impeller on the right hand side of the snowblower. This will straighten the path of the debris into the airstream and increase the performance of the system. We have learned a lot about the dynamics of two-phase flow in regards to snow-entrained air over the course of this project. We have solved the problem at the fan end. This should solve the problem at the snowblower end. This is a significant design change that will have to be done at CRREL if the decision is to proceed. A modified snowblower can be shipped to Antarctica for integration with the tunneler.

The attachment point between the snowblower and the ejector tube is another highly stressed point in the design. The current V-clamp connection is very strong, but continued stressing results in eventual failure. This has been addressed both by John Wright's crew and CRREL's, but a stronger joint is needed. Although this can be done without modifications to the snowblower, the best results will be achieved if the connection point is redesigned and incorporated into an offset-impeller snowblower.

Supporting the nesting ejector tubes near the tunneler cab will help reduce the load on both the snowblower frame and the connection point on the snowblower. A preliminary design was done after the 1999 retrofit deployment but never implemented.

4) *General hydraulics*: The hydraulics on the drum and snowblower circuits have been problematic from the start. Many of the problems have been ironed out over the course of the project and the systems greatly simplified. Reliability is still unsatisfactory, however.

Most of the components in these two circuits are industrial. That is what we were familiar with at the time of the design. What is required are mobile hydraulics. The CI pumps are a move in that direction. So would the use of the Eaton or White drum drive motors. To round out the circuit, the solenoid-actuated directional control valves in this and the snowblower circuits should be replaced with open-center manually actuated valves located in the cab. These will allow flow to be eased to the hydraulic motors, avoiding mechanical and thermal shock. There will be no problems associated with sticking spools as the open centers of these valves will not dead-head the circuits and blow hoses or worse. The pressure relief valves should also be replaced with heavy duty mobile models, and some redundancy built into the circuits.

5) *Pump alignment*: Pump alignment is a problem due to the restricted accessibility of the mounting area, especially during down-hole repairs. Problems associated with the couplers can be minimized if the pump and motor shafts are well aligned. The use of an alignment fixture for the initial alignment of the system components will greatly aid in this process. With the shafts correctly aligned, mounting shims can be made, dowel holes can be drilled, and alignment dowels installed to make quick and accurate removal and reinstallation of the

pumps possible. Better alignment will result in less stress at this connection point and longer life for the coupler and pump components.

Recommendations

The following recommendations are made in order of priority and ease of implementation as I see it at this time. John Wright may assign other priorities to these recommendations or add some items of his own to the list. As he has had the most recent experience with the equipment, his recommendations should be given at least equal weight as these.

1. Replacement of drum drive motor assembly. WSI Von Ruden model 35S-208-A-12-A (Spare motor is P/N 35S-R-12-A) or White model DT28-06-25-5-R3 or Eaton Series 10000 M/N 119-1029 (these preferred).
2. Fabrication of an alignment jig for the electric motor-to-pump connections (CRREL).
3. Replacement of solenoid control valves with manual 3-way diverter valves: Parker P/N BV3D-16-S-1-K-K-2-N (Valve); Parker P/N SK-BV3D-16-S-1-K-K-2-N (Seal kit).
4. Replacement of pressure relief valves: DANA/Chelsea P/N RPL-16-A-G (2750 psi @ 20 gpm); Drum circuit / (2000 psi @ 9 gpm); Snowblower circuit; Cross P/N RV-23D (snowblower) and RV-23F (tunneler); Eaton M/N 32112-GAL (snowblower circuit) and M/N 32112-GAS (drum circuit).
5. Replacement of outer (snowblower) CI tandem gear pump with ¾-in. unit.
6. Redesign of connection point between the snowblower and the ejector tube (at CRREL).
7. Finish the design of ejector pipe support fixture, build one (at CRREL), and install it.
8. Rebuild snowblower for offset impeller operation. Incorporate a new connection point for the ejector tube (at CRREL).

APPENDIX D: TUNNELER DOWNTIME ITEMIZATION—2001–2002 SEASON

The following table is from the tunnel foreman's after-action report from the 2001–2002 season (Wright 2002). It contains a detailed list of all the non-maintenance incidents resulting in work stoppage during that season. Comparison of this report with that of Appendix A indicates the progress made towards rectifying problems with the tunneling machine. This can be directly attributed to the installation of the correct drum drive pump and the more accurate mounting of the pump to the drive motor, per instructions from the CRREL after action report (Appendix C). The table is copied directly from the foreman's report.

Table D-1. Annotated equipment downtime table.

Date	Problem Area	Comments
Nov 20	Tunneler	Flex couple failure. This had been a new replacement on Nov 12. Replaced same with the last new replacement. 2 ½ hour down
Nov 21	Surface Fan Snowblower	Replace worn belts Cutting blade fell off, re-bolted same, welded later while in shop. 2 ½ hours down.
Nov 27	Tunneler	Flex couple failure. Given lathing on splined pump shaft, opt to run with last years oversized CI drum pump. In-tunnel repair attempts precipitated a cascade of failures, including cold soaked machine and circuit breaker failures. Tunneler ultimately removed to Heavy Shop to await arrival of flex couples for use with a new pump. Machined pump mounting bracket at this time. Tunneler come out of shop and back in the tunnel business on Dec 07. Crews excavate Tunnel B in the meantime.
Dec 14	Snowblower	Weldment on Snowblower lift mechanism breaks. Repair and deployment to Tunnel D by Dec 17
Dec 27	Duct System	Sleeping duct-tender syndrome leads to tearing flex duct in transition sled. 4 hours down for repair.
Dec 28	Snowblower	Pin ears on rear of extend cylinder break. Took cylinder to shop for repair. 5 ½ hours down
Dec 28	Tunneler	Hose burst, repair and top hydraulic tank. 4 ½ hours down
Jan 01	Tunneler	Hose burst, repair. 1 ½ hours down.
Jan 02	Snowblower	Broke hinge pin on lift mechanism, repair. 1 ½ hours down

Date	Problem Area	Comments
Jan 14	Tunneler	Repair manual boom lock pin and ears damaged by operator error. 4 hours down.
Jan 18	Tunneler	Manual boom lock broken again beyond immediate repair, operator error again but different operator. Go to using wood 4x4 stull for boom prop. No down time.

APPENDIX E: UNCONFINED COMPRESSIVE STRENGTHS AS A FUNCTION OF DEPTH AND DENSITY OF SNOW CYLINDERS TAKEN FROM A SNOW MINE AT SOUTH POLE (FROM GOW AND RAMSEIER, 1964).

Sampling Depth (m)	Density (kg/m^3)	Strength (MPa)	Sampling Depth (m)	Density (kg/m^3)	Strength (MPa)	Sampling Depth (m)	Density (kg/m^3)	Strength (MPa)
2.59	447	0.34	11.13	483	1.17	16.01	521	1.53
3.05	442	0.32	11.74	501	1.35	16.01	507	1.26
3.05	433	0.26	11.74	495	1.11	16.17	522	1.45
3.20	439	0.19	11.74	508	1.45	16.17	540	1.72
3.51	445	0.38	12.05	516	1.46	16.32	530	1.65
3.51	445	0.28	12.05	505	1.47	16.47	524	1.50
4.27	435	0.31	12.20	514	1.58	16.47	527	1.35
4.27	418	0.23	12.20	511	1.26	17.08	526	1.27
4.42	418	0.30	12.51	496	0.82	17.08	536	1.46
4.73	441	0.25	12.51	482	1.00	17.08	529	1.35
4.73	441	0.28	12.66	457	0.81	17.54	519	1.63
5.34	442	0.32	12.96	499	1.11	17.69	535	1.46
5.34	423	0.37	13.12	482	0.95	18.00	566	2.09
6.10	429	0.29	13.42	492	1.17	18.30	537	1.58
6.41	441	0.42	13.42	512	1.44	18.61	543	1.79
6.41	474	0.59	13.42	487	0.99	18.91	539	1.57
6.41	469	0.56	13.42	498	1.20	18.91	551	1.89
6.56	452	0.47	14.03	513	1.00	19.06	541	2.06
6.71	427	0.39	14.03	501	1.21	19.22	560	2.27
6.71	484	0.85	14.03	505	1.22	19.37	543	1.80
6.71	461	0.59	14.03	505	1.23	19.52	550	1.82
7.02	463	0.57	14.34	505	1.40	19.52	540	1.20
7.02	475	0.50	14.49	524	1.44	19.67	556	2.18
7.02	462	0.73	14.49	530	1.60	19.83	549	1.92
7.17	493	0.75	14.64	510	1.42	19.98	540	1.54
7.17	473	0.71	14.64	517	1.41	20.13	545	1.67
7.78	476	0.82	14.64	513	1.23	20.13	553	1.95
7.78	460	0.59	14.79	517	1.68	20.44	558	1.79
7.93	485	0.66	14.95	505	1.35	20.44	560	1.77

Sampling Depth (m)	Density (kg/m^3)	Strength (MPa)	Sampling Depth (m)	Density (kg/m^3)	Strength (MPa)	Sampling Depth (m)	Density (kg/m^3)	Strength (MPa)
8.54	477	0.67	15.10	517	1.50	20.74	545	2.03
8.54	483	0.76	15.10	516	1.54	20.74	554	2.15
8.85	486	0.77	15.25	492	1.09	20.89	556	1.89
8.85	470	0.61	15.25	501	1.08	21.05	558	2.10
8.89	501	0.97	15.40	508	1.32	21.20	548	1.83
10.22	506	0.85	15.55	504	1.35	21.35	560	1.66
10.22	408	0.85	15.86	528	1.64	21.35	567	1.45
10.98	478	0.67	15.86	537	1.54	21.66	523	1.57
10.98	489	0.96	15.86	540	1.85	21.66	534	1.27

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U.S. Army Engineer Research and Development Center
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14. ABSTRACT

Locating utilities on the surface at the United States' Amundsen-Scott South Pole Station causes many maintenance problems unique to that environment. The extreme low temperatures, drifting snow, and long, dark winters all restrict easy access to these critical components for most of the year. To avoid these problems, a tunneling system to drive tunnels in the dense, hard firn at the South Pole was designed and built for the National Science Foundation, Office of Polar Programs. From 1996 through 2002, a series of 2 ¥ 3-m tunnels were driven for the water system for both the current station and the new station at the pole. This report describes the design and operational problems that were addressed while driving these tunnels at Pole.

15. SUBJECT TERMS

Antarctica; Design; Firn; Operation and performance analysis; South Pole; Tunneling; Tunnels

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