A new 122 mm electromechanical drill for deep ice-sheet coring (DISC): 5. Experience during Greenland field testing

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ABSTRACT. The Deep Ice Sheet Coring (DISC) drill developed by Ice Coring and Drilling Services under contract with the US National Science Foundation is an electromechanical ice-drill system designed to take 122 mm ice cores to depths of 4000 m. The new drill system was field-tested near Summit camp in central Greenland during the spring/summer of 2006. Testing was conducted to verify the performance of the DISC drill system and its individual components and to determine the modifications required prior to the system's planned deployment for coring at the WAIS Divide site in Antarctica in the following year. The experiments, results and the drill crew's experiences with the DISC drill during testing are described and discussed.

INTRODUCTION

In order to verify the performance of the newly completed Deep Ice Sheet Coring (DISC) drill system (Mason and others, 2007; Shturmakov and Sendelbach, 2007), a test season was conducted at Summit Greenland during the boreal summer of 2006. Site preparation for the 2006 testing season began in the summer of 2005. That year, three people from Ice Coring and Drilling Services (ICDS) assisted VECO Polar Resources (VPR), the logistics provider for the US Arctic program, with construction of a 9.8 × 30.5 m steel-framed tent structure to house the drilling equipment and provide protection from the weather (Fig. 1). Following construction of this shelter, ICDS drilled, reamed and cased the pilot hole. The pilot hole was drilled to 103 m depth, and casing was set to 31.2 m depth. An A-frame crane (Fig. 2) used for lifting and placing drill components was also assembled. VPR's construction group excavated an 8.0 × 3.6 × 1.7 m deep cut-out in the snow for the winch (Fig. 2), a 5.9 × 1.4 × 1.3 m deep cut-out for the tower base and a 10.8 × 1.2 × 9.4 m deep slot for the drill tower.

In March 2006, 195 m^3 of equipment began their journey from ICDS in Wisconsin, USA, to Summit camp in preparation for the upcoming test season. The first five members of the ICDS test crew arrived at Summit camp in late April. The first few weeks of the season were spent preparing the DISC drill building for the drill installation and assisting VPR personnel with the installation of the generators and electrical systems. During the second week of May the rest of the test crew arrived and assembly of the drill began. Within 2 weeks the drill installation was complete and commissioning of the drill system had begun (Fig. 3). Over the next several days, mock drill runs were conducted in the pilot hole to permit the drillers to gain familiarity with the system before beginning actual coring. On 1 June 2006 the DISC drill recovered its first core (Fig. 4).

Fig. 1. DISC drill enclosure.

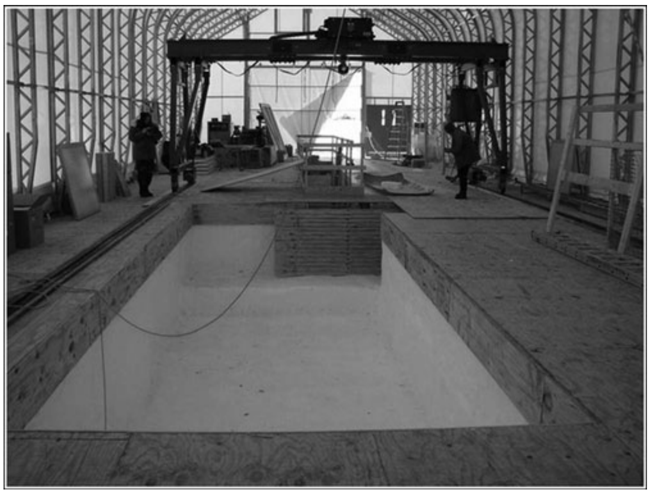

Fig. 2. Floor cut-outs and A-frame crane.

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Fig. 3. Inside of the operational DISC drill site.

Fig. 4. Drill crew with the first core.

DRILLING

The drilling portion of the test season was 6 weeks long. All ICDS personnel worked on a single shift for the first week while initial start-up procedures were worked out. After this the crew was split, and testing/drilling continued in two 10 hour shifts. This mode continued for 2.5 weeks, after which scheduling returned to a single shift for the remainder of the season. This ensured that drilling would be ongoing during a planned operational review visit in mid-July by the US National Science Foundation, the West Antarctic Ice Sheet (WAIS) Divide Science Coordinating Office and the ICDS management.

A total of 286 drill runs were completed during the test season, and a final depth of 765.8 m was achieved. Drill cycle time averaged 66.7 min over the 89 runs made from 395 to 610 m. This average cycle time comprises 17.5 min for surface operations, 23.6 min for tripping down-hole, 7.7 min for coring and 17.9 min for tripping back to the surface.

The drill team settled quickly into a routine aided by the efficient layout of equipment and workspaces within the DISC structure. Drillers rotated daily through the various tasks to relieve the repetitiveness of day-in and day-out drilling. Surface operation improvements were identified and will be implemented during production drilling at the WAIS Divide site.

DRILLING FLUID

Isopar K was the drilling fluid used for the Greenland test season. It is the base component of the two-part drilling fluid planned for use at WAIS Divide. The densifier (HCFC 141b) planned for use at WAIS Divide was not used in Greenland for environmental considerations. The density of Isopar K is 0.76 g cm^{-3} and, as a result, the borehole was under-pressurized during the test season. While this resulted in an accelerated borehole-closure rate, this was not a concern since there was no plan to re-enter the borehole in a later season. From a handling and a health and safety standpoint, Isopar K was found to be an unobjectionable fluid to work with. It does not readily evaporate in Arctic conditions and it has no odor. Aside from gloves, no other personal protective equipment was required while handling the fluid, and no ill effects were reported as a result of working with it on a daily basis.

CORING

The DISC drill was designed to recover a 4 m core in a single run (Mason and others, 2007; Shturmakov and others, 2007). Initial drill runs indicated that the drill was losing penetration before this design target could be met. As a result, only shorter ice cores were recovered during initial drill runs. The average length of core during the test was 2.49 m and the longest core drilled in one run was 3.08 m. With cores approximately 3 m long, the screen section was already filled with chips. The average density of the chips in the screen section was 0.38 g cm^{-3}. In order to determine whether screen capacity was the limiting factor for core length, the screen section was extended by adding two screen modules (approximately 1.5 m). Core lengths did not improve with the longer screen section, nor were the added screens being filled with chips. This indicated that pumping capacity might be a factor in limiting core length. Note again, however, that for the Greenland test there was no densifier in the drilling fluid and the density of the Isopar K was only 0.76 g cm^{-3}. The chips, which have a density of approximately 0.92 g cm^{-3}, are denser than the fluid and therefore sink. The screen section is designed to work with neutrally buoyant chips that enter the screen section from the bottom and fill the screens from the top down. Since the chips were denser than the fluid, the pump was required to lift them. A point may have been reached when the pump could no longer lift the weight of the negatively buoyant chips. The inlet to the screen section, consequently, may have become plugged, causing the drill to lose penetration and ending the drill run. Pump efficiency may also decrease as the fluid density decreases. This, in turn, would affect how densely chips pack in the screens. This may have been another factor contributing to the shorter core lengths. Improvements in core length, pump performance, and packing of the chips in the screen section are expected when the drilling fluid is at the near-ice density.

Two ice-coring acceptance tests were completed and passed in accordance with the field test plan. The first was a ductile ice-coring acceptance test and the second was a brittle ice-coring acceptance test. The ductile ice-coring acceptance test required the recovery of three contiguous core segments totaling approximately 12 m in no more than 12 pieces of ice per 10 m section of core. Ice pieces were required to fit together snugly without any gaps, and the core

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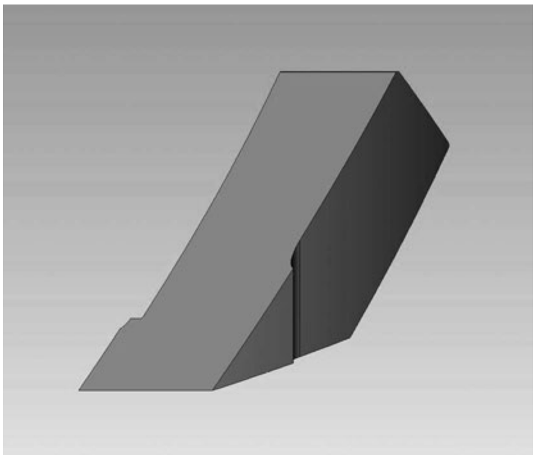

Fig. 5. Sharp-corner cutter.

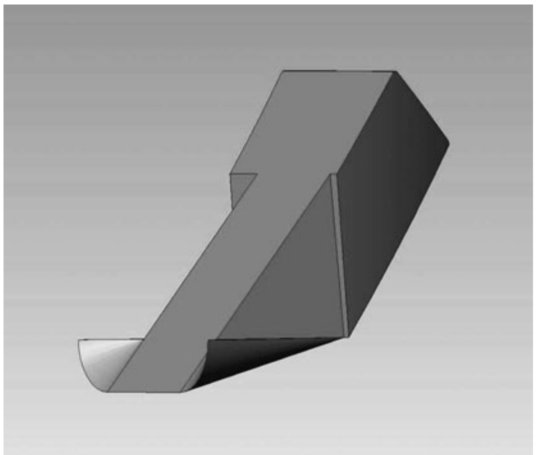

Fig. 6. Scoop cutter.

was to have no micro-cracks that could potentially provide conduits for contamination into the core. Three contiguous 4 m cores were recovered between depths of 457 and 469 m for this test. To recover 4 m cores, two drill runs were made to obtain each core using the following procedure. Core dogs were removed for the first run and only chips were recovered; on the second run the core dogs were replaced and 2 m worth of chips and a 4 m core were recovered. All three cores were recovered without fractures or breaks in them, the core ends fit together snugly, core diameter was 121 mm, and only small, non-critical, surface fractures 0.5–1.0 mm deep were visible.

The second test was a brittle ice-coring acceptance test. The requirements for this test were the recovery of three contiguous core segments totaling at least 4.5 m. We required 80% of the ice to be in pieces larger than 2 L, and ice pieces were to fit together and retain stratigraphic order. Three contiguous 2 m cores were recovered between depths of 733 and 739 m for this test. Each core had one break in it and two of the three had a spall. Surface fractures were again observed.

A requirement to determine the core's in situ azimuth within $\pm 10^{\circ}$ was also satisfied during the test season for the drill system.

CUTTERS

Two types of cutters were tested in Greenland. The first was the traditional sharp-cornered cutter with a 50° cutting face and a 15° relief angle (Fig. 5). The second type was a double scoop cutter. This cutter also has a 50° cutting face and a 15° relief angle, but both the inside and outside edges have been rolled up (Fig. 6).

Overall core quality with the sharp-cornered cutter was good from the outset of testing. The outside of the core was smooth, with the typical light spiral markings showing the cutter pitch (Fig. 7). Undesirable small surface fractures 0.5–1.0 mm deep running with the direction of cut and at 45° to the direction of cut were observed. Initially, a white-colored helical stripe was observed on the cores. By adding more relief to the inside edge of the cutters, the striping and the small surface fractures running with the direction of cut were eliminated. This cutter geometry performed equally well in the ductile and brittle ice zones. A small radius, $\sim$1 mm, was ground on the inside corner of one set of cutters to see what effect it would have on the quantity and orientation of surface fractures. No improvement was observed.

The scoop cutters produced poor-quality core. The surface of the core had a ribbed helical pattern, which appeared to be cutter-speed dependent. In the areas between the helices, gouging from the cutters could be seen (Fig. 8). Beyond the very coarse surface of the core, no other surface fractures were seen. The double scoop design allowed the cutter head to freely cut sideways. Eliminating the outer scoop and possibly providing more guidance for the cutter head may solve the problems we encountered and allow this type of cutter to cut a smooth core.

Four different penetration, shoe heights were tested in Greenland. These yielded pitches of 3.5, 4.5, 5.9 and 9.0 mm. The best drill performance was observed using the 5.9 mm pitch shoes.

CUTTER HEAD

Drill runs typically ended when penetration was lost due to chips packing the cutter head. Fluid flow around the cutters is important to prevent chips from building up. The openings or windows above the cutters, therefore, were enlarged on one drill head to see what effect changing the flow pattern at the head would have on core length. Core lengths obtained with the modified head were no different than with the unmodified head. This indicated that, with the current drill configuration and drilling conditions, fluid flow at the cutter head was not the limiting factor on obtainable core length.

Core dog cages were also modified to facilitate easy removal of the core from the core barrel. In the original configuration, chips could pack behind the core dogs which would then prevent them from retracting when pushing out a core. An opening was cut in each cage behind the core dog to provide an exit path for the chips. This modification worked very well.

FLUID PUMP

For the test the pump was run at speeds between 1200 and 3000 rpm. The best pump performance was between 2100 and 2300 rpm. This corresponded to flow rates of 284–322 L min^{-1} and pressures of 41.4–55.2 kPa when pumping water. When running the pump at speeds above 2300 rpm, the cores recovered were broken and had a pack of chips

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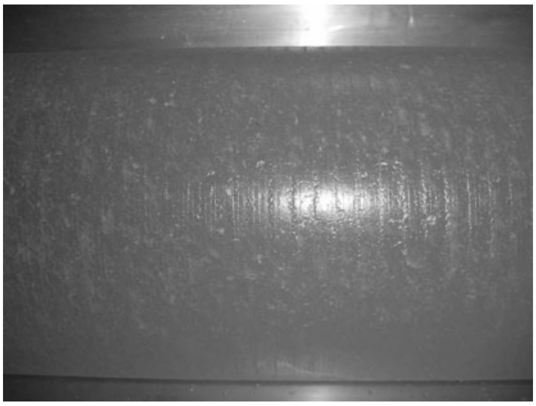

Fig. 7. Core cut with sharp corner cutters.

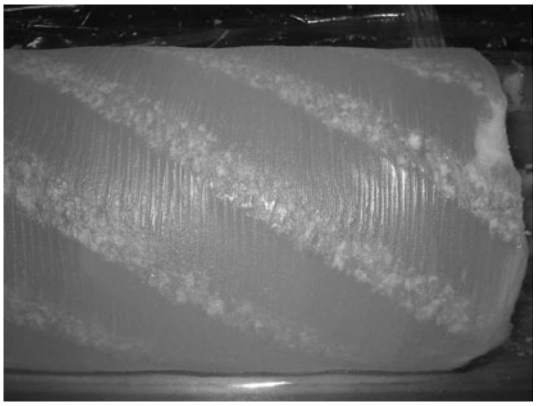

Fig. 8. Core cut with double scoop cutters.

between the pieces. We believe this phenomenon was the result of the pump generating enough suction to lift the core inside the core barrel and pull chips into the breaks between the core pieces.

CUTTER SPEEDS

Cutter speeds were tested from 60 to 110 rpm. A speed of 80 rpm gave the best results. There is a maximum amount of power that can be delivered to the drill motor section and it has to be shared between the cutter and pump motors. This is a give-and-take situation in which a balance must be achieved between the power used by the cutter motor and the power used by the pump motor. Running the cutter at 80 rpm gave the pump motor a comfortable amount of excess capacity to operate.

CONTROL SYSTEM

Operation of the winch and drill took place from the control room through a computer interface. The winch also had a manual control station outside the control room that worked independently of the computer system; this makes it possible to bring the drill to the surface should the computer system fail. One operator can run all winch controls, but the presence of a second person to help collect drill-run data proved to be more efficient. The control system automatically logs all data from the drill run, but filling a drill-run data sheet with some basic data was a handy reference tool. Drill-run data sheets were in paper format and filled out manually. In the future, the drill-run data sheets will be generated automatically, with provision for the operator to add comments. A printer will be available to print hard copies as deemed necessary. The winch control software used in Greenland was still under development. It was fully operational but not user-friendly. Before deployment to WAIS Divide the software will be completed and some features will be automated as a result of the operating experience gained during testing in Greenland. During the test the appearance of the control screens was modified to make them more accessible and easy to use.

INSTRUMENT SECTION

A few problems were encountered with the instrument section during the season (Mortensen and others, 2007). In two different instrument sections, one of the connectors on the motor driver boards had bad solder joints which caused an intermittent motor-starting/running problem that worsened with time. This was a difficult problem to troubleshoot, but once it was found and fixed, the cutter and pump motors ran well for the remainder of the season. Noisy sensor signals were also problematic. The noise translated into feedback data that were difficult to interpret. Some filtering was added in the field, which helped clean up the signals, but further work on noise filtering is needed before the drill is placed into production drilling. As drilling progressed and fluid pressure increased with depth, the instrument sections' bulkhead electrical feed-through began to leak. The connectors were found to have the wrong pressure rating. While they were environmentally sealed, they were not rated for operational down-hole pressures. Fortunately, the small amounts of Isopar K leaking into the instrument section did not damage the electronics.

WINCH

The winch used in the DISC drill system comprises four major components. These are the winch drum, level wind, motor section and control cabinet. Because of its size and weight, the winch must be broken down into these four pieces for shipping. Once on site, the components are moved into final position using a gantry crane.

At the beginning of the season the winch pit temperature was –30°C, and lubricant in the level-wind and penetration-drive gearboxes was so thick that the motors had difficulty operating. The problem was solved by changing the lubricant and adding heat tapes to the motors and gearboxes. During drilling operations, the level-wind drive intermittently faulted and stopped when winching speeds approached 0.7 m s^{-1}. This fault occurred only when running at speeds around 0.7 m s^{-1}, and the system ran without difficulty at slower or faster rates. With the exception of this problem, the winch ran reliably for the entire test season.

The maximum obtainable cable payout speed was 1.2 m s^{-1}. Cable payout speed is limited by the speed at which the drill can fall through the fluid-filled borehole. Paying cable out faster than the drill is descending creates a very dangerous situation since the slack cable will tangle on itself in the borehole. This situation was experienced during testing, and the end result was a knot in the cable. The strength members of the cable (Shturmakov and Sendelbach, 2007) were not damaged and the sonde was safely recovered in this incident. It may be possible to achieve

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Fig. 9. Screen-cleaning system being used manually.

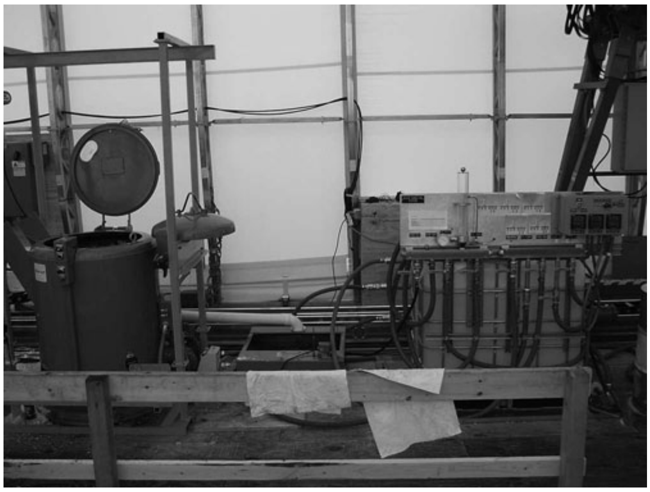

Fig. 10. Centrifuge and fluid-handling system.

higher cable payout speeds by running the pump while descending; however, we were unable to complete this test due to the knot in the winch cable. Once a knot is put in the cable, the only way to remove it is to cut the cable and re-terminate the end above where the knot was located. Winch speed tests were conducted after all drilling was completed, so cable re-termination was not done in the field.

A test of the speed at which the sonde could be raised from the borehole indicated that a speed of approximately 2.9 m s^{-1} could be obtained.

While the winch functioned satisfactorily in Greenland, modifications to the level wind, motor section and control system are planned before it is deployed to WAIS Divide. These modifications will improve the efficiency and long-term reliability of the winch.

POWER REQUIREMENTS

Power to run the DISC drill operations at Summit Camp Greenland was provided by two 125 kW diesel generators. Derated for the altitude at Summit, the maximum power output of each generator was approximately 104 kW. Only one generator was run at a time, while the other was maintained as a back-up. Average power consumption without the winch running was 12–20 kW. The total average power consumption with the winch running at speeds of up to 0.7 m s^{-1} at depths of 700–750 m was 18–30 kW. The estimated power consumption with the 112 kW winch motor running to its full rated capacity is 130–135 kW. These generators were therefore undersized for our peak load, but no difficulties were encountered since the winch was not run at its full capacity.

SURFACE OPERATIONS

Once the drill arrives at the surface and is tilted to a horizontal position, the screen barrel section, which contains eight cylindrical screens, is removed from the drill string and moved to the screen-cleaning station using a gantry crane fitted with a barrel-lifting and -rotating fixture. A duplicate barrel with empty screens is then picked up and returned to the drill to be readied for another run. As a new drill run is being started, an operator initiates the screen-cleaning process. First the check valve is removed and a lead-in ring is inserted into the down-hole end of the barrel. The operator then moves to the other end of the barrel where a start button is pressed to begin a cleaning cycle. A conveyor situated parallel to and behind the barrel transports a clean screen to the down-hole end of the barrel. When the screen arrives it is automatically loaded onto a transfer stage which translates the screen sideways and reinserts it into the barrel. This, in turn, pushes a screen full of ice chips out onto a tray in front of the operator. The operator then pivots the tray vertical and plunges the chips from the screen into a hopper. The tray is then returned to its horizontal position and the cleaned screen is placed on the conveyor. The process is repeated seven more times. The lead-in ring is finally removed and the check valve reinstalled. The screen barrel is now ready for another drill run.

During field testing, the screens were easier to clean if the fines sticking to the inside of them were melted between drill runs. To accomplish this, the empty but not totally clean screens were taken outside and placed in front of the generator load bank. The ambient warm air quickly melted out any remaining chips and dried the screens. A spare set of screens was put into the rotation so a set of clean, dry screens was always ready to insert. Since the screens were now taken out of the automated system to permit melting the fines, we found that manually pushing the clean screens into the barrel was more efficient then reinserting them with the automated system (Fig. 9).

Once the ice-chip/drilling slush was collected from the screens it was sent to the centrifuge (Fig. 10). The hopper was loaded into the centrifuge with an overhead chain hoist. After a 2 min cycle time, the hopper was hoisted from the centrifuge and emptied. This process removed 90% of the drilling fluid from the chips. Finally, the weight of the centrifuged chips was recorded before they were disposed of outside at a designated dumping site in order to provide an indication of the drill's efficiency in removing them from the borehole.

All new drilling fluid and fluid recycled from the centrifuge was run through the fluid-handling system (Fig. 10). The main components of this closed system are a 1041 L tank, 0.4 kW circulation pump, manifolds, flowmeters with batch controls, and a station for measuring specific gravity of the fluid. By setting the levers on the manifolds, fluid can be directed from storage barrels into the fluid-system holding

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tank. Batch controllers are programmed to bring in the desired quantity of drilling fluid (Isopar K) and densifier (HCFC 141b). A timed mixing cycle pumps fluid from the bottom of the tank and returns it to the top. An enclosed system for measuring the specific gravity of the fluid mix draws sample off the top of the return manifold, and if necessary the mix is adjusted. The fluid is then ready to be pumped into the borehole by a third batch controller. During the Greenland test we found that the fluid pump had difficulty self-priming when initiating a fluid draw from the storage barrels. In instances when the pump was able to prime itself, the pumping rate was unacceptably slow. We are investigating solving this problem by adding barrel pumps to the system.

WORKSHOP

In an effort to minimize downtime that would result from the need to repair or modify the drill equipment in the field, the DISC drill system includes a portable machine shop and electronics shop. The shop was built inside a 6 m shipping container with fold-out side-walls that effectively triple the usable interior space (Fig. 11). A milling machine and lathe are mounted in the center of the shop. Other shop equipment includes a tungsten inert-gas (TIG)/stick welder, plasma cutter, metal-cutting bandsaw, bench grinder, vertical belt sander, arbor press, hand-tool chest, machinist-tool chest, tooling for the machine tools, and workbenches. The electronics area includes a tool chest for related tools, drill-cable terminating equipment, fiber-optic terminating and test equipment, test meters, power supply to run the instrument section on the bench, and a workbench with provision for working on equipment sensitive to electrical static discharge. All equipment fits within the closed container for shipping.

SAFETY

Safety is the most important aspect of the DISC drill operation. The drill system can present many hazards to the operators if they are not properly trained or if operating procedures are not followed. Potential hazards have been identified and personal protective equipment, signage, safety equipment and training courses were provided for the drill crew. At the beginning of the test season, on-site weekly emergency exercises were conducted to further train the drill crew and camp staff on the proper response to a variety of emergency situations. Daily inspections were conducted to ensure walkways were kept open, signs were visible and safety equipment was in place.

Vapors from the drilling fluid are heavier than air, so two different ventilation systems were installed in the drill building to ensure vapors did not accumulate inside the structure. The first system consisted of six floor-level exhaust fans that pulled fresh air in at the ceiling level and exhausted it outside at the floor level. These fans provided six air exchanges per hour. The second system was an exhaust fan mounted on a stand outside the building with ductwork running to the bottom of the slot. This fan ran continuously, providing eight air exchanges per hour to remove any vapors that collected in the winch pit or slot areas. A four-channel air monitor was mounted in the control room to monitor air quality in the drill building. It continuously monitored oxygen levels, lower explosive limits and permissible exposure limits in the control room, screen-cleaning area, winch pit and slot. The slot is classified as a confined space, so a permit must be issued prior to each entry. Each entrant must also have a spotter on the surface and wear a fall-arrest harness connected to a retractable lifeline, hard hat, two-way radio and clip-on oxygen monitor.

Fig. 11. Portable machine shop and electronics shop.

Fire poses a serious risk to people in remote polar camps like Summit. There is limited heated living space, people are working in close quarters, and large-scale firefighting equipment is not available. Maintaining a clean and orderly work area and carefully monitoring the use and storage of flammable liquids is the first line of defense against fire hazards. The drill building was equipped with a fire-alarm system to notify occupants, fire extinguishers were available near exits in high-risk areas, and a large 65 lb (29.5 kg) Halotron fire extinguisher was kept near the winch.

PACKING

Disassembly and packing of the DISC drill system began on 14 July 2006. The original schedule allowed 13 days for disassembly and packing, but the job was completed in 6 days with a crew of eight people. The drill crew departed Summit on 25 July.

CONCLUSION

The DISC drill test season at Summit Greenland was successful. Although we were not able to recover a full 4 m core in one run, all other testing performance goals were met and in many cases exceeded. Core quality and the drill's ability to drill brittle ice were excellent from the start. There were problems and challenges, but, given we were testing a completely new drill system that had never been fully assembled and operated, the season went extremely well. A wealth of test data and a good understanding of the strengths and weaknesses of the drill system were acquired. This will allow ICDS to make improvements necessary for the drill's successful operation at WAIS Divide.

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series (Shturmakov and others, 2007), we also thank VECO Polar Resources for ongoing help and logistics support during the Greenland test season.

REFERENCES

Mason, W.P., A.J. Shturmakov, J.A. Johnson and S. Haman. 2007. A new 122 mm electromechanical drill for deep ice-sheet coring (DISC): 2. Mechanical design. *Ann. Glaciol.,* **47**, 35–40.

Mortensen, N.B., P.J. Sendelbach and A.J. Shturmakov. 2007. A new 122 mm electromechanical drill for deep ice-sheet coring (DISC): 3. Control, electrical and electronics design. *Ann. Glaciol.,* **47**, 41–50.

Shturmakov, A.J. and P.J. Sendelbach. 2007. A new 122 mm electromechanical drill for deep ice-sheet coring (DISC): 4. Drill cable. *Ann. Glaciol.,* **47**, 51–53.

Shturmakov, A.J., D.A. Lebar, W.P. Mason and C.R. Bentley. 2007. A new 122 mm electromechanical drill for deep ice-sheet coring (DISC): 1. Design concepts. *Ann. Glaciol.,* **47**, 28–34.