A new 122 mm electromechanical drill for deep ice-sheet coring (DISC): 1. Design concepts

Alexander J. SHTURMAKOV, Donald A. LEBAR, William P. MASON, Charles R. BENTLEY

Ice Coring and Drilling Services, Space Science and Engineering Center, University of Wisconsin–Madison, 1225 West Dayton Street, Madison, WI 53706-1612, USA
E-mail: alex.shturmakov@ssec.wisc.edu

ABSTRACT. The Deep Ice Sheet Coring (DISC) drill, developed by Ice Coring and Drilling Services (ICDS) under contract with the US National Science Foundation, is an electromechanical drill designed to take 122 mm diameter ice cores to depths of 4000 m. The conceptual design of the DISC drill was developed in 2002/03 based on science requirements written by K. Taylor and the United States ice-coring community and on engineering performance objectives. Detailed design of the drill began in June 2003. Special attention was paid to building safety into the design and operation of the drill system. The drill was designed and manufactured by a team of engineers and technicians from the University of Wisconsin–Madison and various subcontractors with assistance from the science community, the European ice-drilling community and polar logistical support organizations. ICDS successfully tested the drill in Greenland in 2006 and will continue its development to meet the science objectives of the West Antarctic Ice Sheet Divide Ice Core Project.

NEED FOR A NEW US DEEP ICE-CORING DRILL

After completion of ice coring at Siple Dome during the 1998/99 Antarctic field season, it became apparent that the deep ice-coring drill used by the ice-coring community was in poor condition and in need of repair/modification or replacement. In the boreal summer of 2000, the US National Science Foundation (NSF) awarded the University of Wisconsin–Madison a contract for ice-coring and drilling services, and the university formed the Ice Coring and Drilling Services (ICDS) group within the Space Science and Engineering Center. At its first meeting, the ICDS Science Advisory Board urged the NSF to task ICDS to study alternatives for deep ice-coring drills. Subsequently, Eustes and others (2001), from the Colorado School of Mines (CSM), recommended that a ‘second-generation’ deep ice-coring drill be developed and that the drill system be designed to incorporate technologies that would allow directional coring operations.

The NSF tasked ICDS to begin the conceptual design of a new US deep ice-coring drill during federal fiscal year 2002 (1 October 2001 to 30 September 2002). Using the CSM report as a guide, a team of ICDS engineers, scientists representing the Ice Core Working Group (ICWG), drillers and CSM consultants closely examined the characteristics of the existing deep ice-core drills and new technologies to develop concepts that would fulfill the US science community’s needs. At the ICWG annual meeting in March 2003, the ICDS team presented several drill design alternatives that would meet the science needs. In May 2003, on the recommendation of ICWG, the NSF directed ICDS to begin detailed design of the Deep Ice Sheet Coring (DISC) drill, capable of producing a 100 mm diameter core. Detailed design of the drill began in June 2003 and included features found on existing deep ice drills such as the EPICA (European Project for Ice Coring in Antarctica) drill (Johnsen and Hansen, 2008), the Russian KEMS drill (Kudryashov and others, 2002) and the American ‘5.2-inch drill’ (Kelly and others, 1994), as well as innovations made possible by state-of-the-art electronics and material science. The diameter was increased to 122 mm in February 2004. Scientists wanted a core this size to provide up to 9 cm^2 per core cross-section for melt sticks and up to 16 cm^2 per core cross-section for non-melt science. This would be a significantly larger amount of ice than had previously been available from a 100 mm diameter core.

DESIGN CONSIDERATIONS

The design of the DISC drill was driven by the requirements of the scientists who would be using the cores and the borehole produced by the drill. In November 2002, ICWG approved the science requirements drafted by K. Taylor. The main requirements, some of which may not be achievable, for the drill and the collected ice core, were:

Ice core to be collected to a depth of 3800 m with 100% recovery.

To drill 50 m of ice containing as much as 5% silt.

To drill in ice that is within 2°C of the pressure-melting point.

Ice core of diameter greater than 98 mm.

Ice core that fits snugly together without gaps.

In non-brittle ice, packed ice core to have no more than 12 pieces of ice per 10 m section of core.

In brittle ice, while there may be many pieces in a single 1 m core segment, pieces must fit together and maintain stratigraphic order. More than 80% of the ice volume must be in pieces that have a volume greater than 2 L.

Borehole inclination to be less than 5% from vertical.

https://doi.org/10.3189/172756407786857811 Published online by Cambridge University Press

Borehole inclination, azimuth and diameter to be determined as a function of depth.

Absolute depth measurement accuracy of 0.02% of depth, with a relative depth measurement accuracy of 20 mm over the length of a drilling run.

Ability to collect additional 'duplicate' core that is at least 80 mm diameter over an interval of up to 150 m and within 20 m of the main borehole using deviation drilling techniques.

Ability to core up to 4 m of bedrock, collect 2 m of unfrozen unconsolidated basal material, and drill through 20 m of sandy ice and through 10 mm of rock pebbles.

Record the following parameters at 10 times per second: depth, drill rotation speed, cutting torque, weight on bit, fluid temperature, and core barrel acceleration.

Of these requirements the essential theme was to produce core of such a quality as to be useful to the scientists.

A major consideration in the design of the drill was the desire to minimize the number of field seasons needed to complete a deep coring project. Major factors in the time needed to complete the coring of a hole to a specified depth are drill cycle time, core length and drill reliability. The drilling cycle time can be defined as the time required to perform the following steps:

Lower the sonde to the bottom of the borehole.

Produce the desired length of core.

Raise the sonde back to the surface.

Perform necessary surface operations that include the removal of the core, cleaning the drill of ice chips, and routine drill maintenance and adjustment.

Once the surface operations are completed, the drill is ready for the next cycle.

The most critical factor in drill cycle time is the amount of time required to lower the drill sonde to the bottom of the hole and to raise the drill back to the surface after the core has been produced. These times become increasingly critical at greater depths. The speed during the descent portion of the cycle ('tripping in') is limited to the speed achieved in free fall through the fluid unless the drill can be 'pumped in', that is using the pump to provide propulsion to achieve descent speeds in excess of those achievable by gravity. Initial hopes for the DISC drill were that the pump could be used in this manner. The speed during the ascent portion of the cycle ('tripping out') is limited by the speed at which the drill winch can be operated. The maximum trip-out speed was seen to be mainly a trade-off between speed and the power required to operate the winch.

The number of cycles for a hole of a particular depth is reduced by taking the longest possible core during each drill run. While longer cores per run increase the time spent producing the core, for deeper holes coring time becomes a smaller portion of the cycle time than the times required to lower and raise the sonde from the bottom of the hole; consequently, the time to complete the hole would decrease. The overall length of the drill will limit the practical maximum length of the core that can be collected during a run. In weighing the trade-offs involved in the design of the drill, ICDS chose a target of 4 m for the maximum core length.

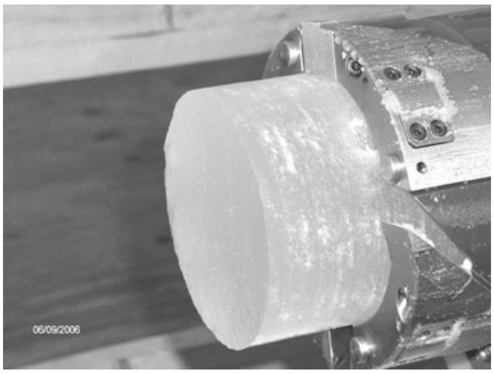

Fig. 1. Cutter head with ice core.

Reliability of the drill can greatly affect the total amount of time required to complete the coring of a hole. ICDS took a two-pronged approach to achieving high reliability of the drill system: (1) ensuring high reliability through quality of design and fabrication; and (2) planning to have adequate spare parts and assemblies available at the drill site.

Finally, the overriding requirement was the ability to assemble, operate and disassemble the drill system in a safe manner.

DRILL SUBSYSTEMS

Eleven subsystems were identified for the DISC drill (Mason and others, 2007; Mortensen and others, 2007; Shturmakov and Sendelbach, 2007). The design of each of the subsystems influenced the design of the others, and consequently much of the design of the subsystems was done concurrently. The subsystems and the considerations that went into their design are as follows.

Drill sonde

The down-hole portion of the drill system, the sonde, more than any other subsystem defines the drill system. The sonde subsystem cuts the ice and collects the core and ice chips. It begins at the cutter head and ends with the connection to the drill cable. The drill was designed to produce a core 122 mm in diameter. The maximum diameter of the drill sonde is 157 mm, and the drill produces a hole 170 mm in diameter.

Maximum core length was set at 4 m; this length provided a reasonable trade-off between the minimization of the number of drill cycles and a manageable length of drill, which in the final design was approximately 16 m.

The drill sonde is modular and consists of six distinct and separable sections:

The *cutter head* assembly (Fig. 1) includes four replaceable cutters, penetration shoes and core dogs. The cutter head is removable from the core barrel, allowing heads to be replaced.

A single rotating *core barrel* (Fig. 2) consists of a series of 276 mm long tube sections mechanically connected together to form the barrel. For a 4 m core a total of 15 sections are used. The barrel can be fitted with a fiberglass core sleeve, which rotates with the core barrel and helps keep fractured core together.

https://doi.org/10.3189/172756407786857811 Published online by Cambridge University Press

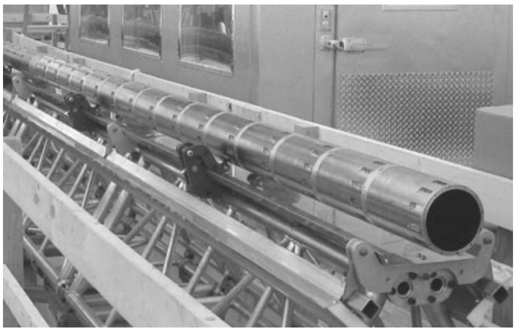

Fig. 2. Core barrel.

The *screen section* (Fig. 3) in which ice cuttings (chips) are collected consists of a housing made up of the same tube sections as the core barrel and a number of 760 mm long screen sections inserted in the center of the screen-section housing. Drill fluid carrying the chips is pumped into the center of the cylindrical screen sections; the chips are trapped inside the screen cylinder while the fluid passes through the screen into the annulus of the screen section up to the suction side of the pump. The required length of screens for a 4 m core was estimated to be 6.1 m. The screen section rotates with the core barrel.

The *motor/pump section* (Fig. 4a and b) of the drill sonde contains the drill fluid pump, the pump motor and the drill cutter motor. The pump is a single-stage turbine pump rated at flow rate of 180 L min^{-1} at a speed of 2400 rpm and is driven by a 2.5 kW d.c. motor through a magnetic coupling. The cutter motor, rated at 1.8 kW at 7500 rpm, rotates the screen section, the core barrel and the cutter head through a 30 : 1 harmonic gear reducer. Separately controllable motors for the pump and the cutter were chosen to provide flexibility, with range of cutter speeds being 0–250 rpm and range of pump rates being 0–750 L min^{-1}. Higher pumping rates are expected to help with the coring of warm ice. It may also be possible to operate the pump to help propel the drill sonde down the borehole, thereby reducing the time required to trip into the hole.

The *instrument section* (Fig. 5) consists of devices for power conditioning and control, communications, sensing and control. Power modules supply power to the

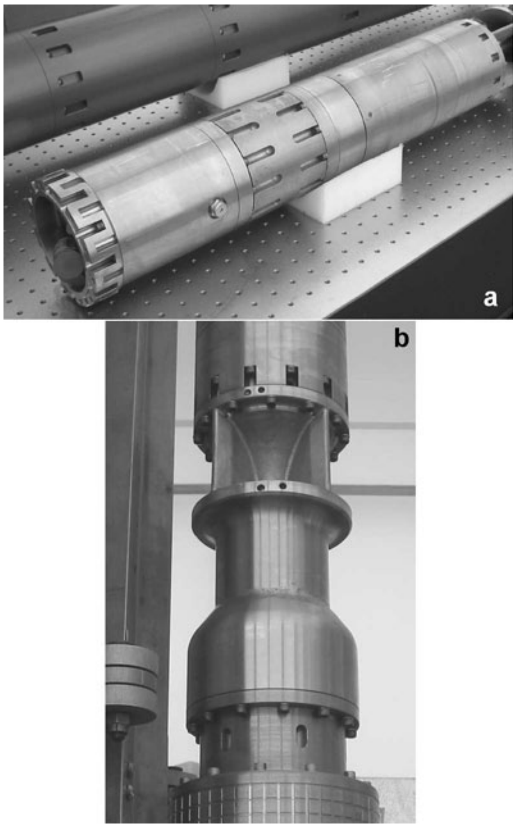

Fig. 4. (a) Motor section; and (b) pump section.

motors and to instruments and controls. Electronic circuits in the instrument section allow for the 'on-board' control of the drill and pump motors and for control of the various sensors in the sonde. 'On-board' micro-processors control and moderate the communication of commands and data between the various sensors and controllers within the drill sonde and the surface.

The *upper section* (Fig. 6) consists of the mechanical, electrical power and optic fiber terminations of the cable that include rotary joints that allow the cable to rotate relative to the drill sonde. The upper section incorporates a mechanical fuse that allows the sonde to disconnect from the cable before the cable reaches its maximum allowable stress; this prevents the cable from being damaged. The upper section also contains the drill anti-

Fig. 3. Screen section.

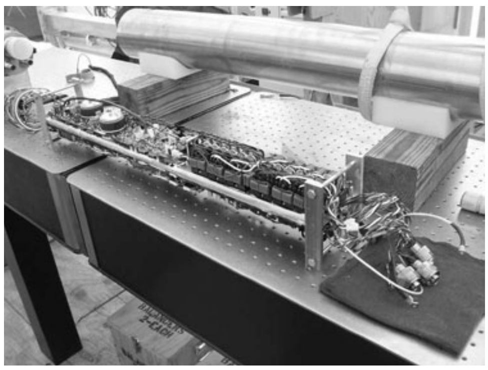

Fig. 5. Drill sonde electronics on workbench, in front of housing.

https://doi.org/10.3189/172756407786857811 Published online by Cambridge University Press

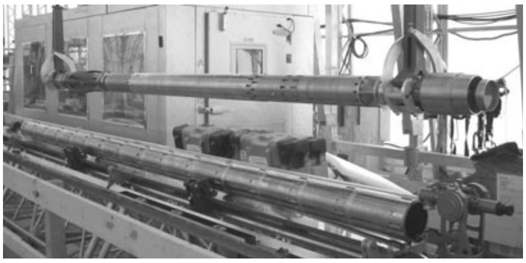

Fig. 6. Upper sonde section and core assembly equipment.

torques, which center the drill sonde in the borehole and provide a torque reaction point to prevent the drill motor from rotating the sonde.

Drill cable

The drill cable (Fig. 7) functions as the tether from the surface to the drill sonde and as a conduit for electrical power and communications. The cable is approximately 15.2 mm in diameter and consists of outer wrapped galvanized plow-steel wires to provide the mechanical strength needed to suspend the sonde, and copper and copper-coated steel electrical conductors for the transmission of power. The center of the cable consists of optical fibers for the high-speed transmission of data between the surface and the drill sonde. The size of the cable was driven largely by the amount of steel needed to provide the required mechanical strength and the need to carry as much as 6 kW of power.

Drill tower

The DISC drill tower (Fig. 8) is approximately 15.3 m long and tilts to allow easy core removal and drill sonde servicing. The tower itself consists of 1 and 2 m long sections bolted together at flanges at the ends of each section. The sections are made of welded tubing and are triangular in cross-section, allowing the sections to be 'unfolded' for storage and transport. A hydraulic ram lowers and raises the tower.

Winch

The cable winch (Fig. 9) is electrically driven and is unusual in that the drum axis is parallel to the drill cable as the cable runs between the winch and tower, with the level wind traversing back and forth across the width of the drum in line with the cable. This configuration allows the winch to be connected to the tower base, resulting in a smaller footprint.

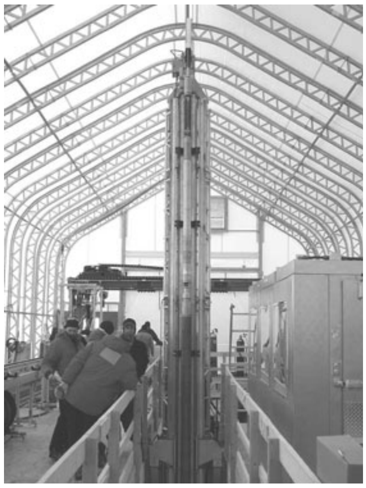

Fig. 8. Drill tower with sonde.

The winch was designed and fabricated by a US manufacturer and modified by ICDS. The overall size of the winch was dictated by the maximum hole depth specified in the science requirements (3800 m) and the diameter and design of the drill cable. The winch currently has two electric motors driving the drum: a 112 kW motor capable of raising the sonde at speeds of up to 3 m s^{-1} and a 2.24 kW motor used for 'fine' control while drilling and positioning the drill on the tower. A dedicated microprocessor is used to control the winch, and the winch can be operated in either a local–manual mode using a pendant or through the main control computers in the control room.

Surface power supply

The surface power supply provides the power to the drill sonde via the cable. The supply comprises modified versions of two commercially available power-supply modules with outputs of up to 1000 V d.c. The high d.c. voltage provides for at least 300 V d.c. at the drill sonde after losses in the drill cable.

Control system

Control for the entire drill system (Fig. 10) is PC-based with a user interface that employs LabVIEW. Data from the drill sonde, the tower and the winch are displayed, and drill control parameters set using the computers. The computers

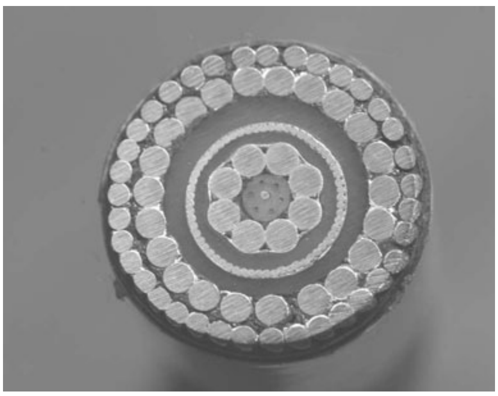

Fig. 7. Cable.

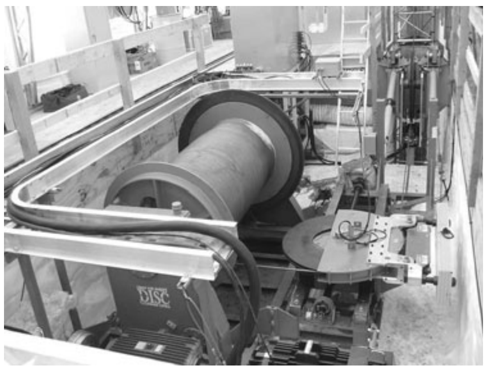

Fig. 9. Winch on the left and level wind in right foreground; cable runs around level-wind sheave to the second sheave at base of drill tower, barely visible in the background.

https://doi.org/10.3189/172756407786857811 Published online by Cambridge University Press

Fig. 10. Inside of control room.

Fig. 12. Screen-cleaning station; a screen section is laid out to the left of the barrels.

along with other equipment are housed in a 1.78 m × 3.53 m × 2.00 m insulated and temperature-controlled room which is positioned to allow the operators to observe the drilling equipment and operations.

Core handling

Because of the layout of the drill equipment and the core-handling process developed by the US National Ice Core Laboratory (NICL), the core barrel must be rotated (Fig. 6) before the core is pushed out of the barrel into the core-processing ice tray. Once the core barrel is disconnected from the rest of the sonde, it is lifted and rotated 180° using a specially designed lifting device attached to a 2 ton gantry crane. The barrel is then lowered onto a table consisting of several sections of the tower modules that have been connected and leveled. The core is then pushed from the barrel from the upper end onto a tray on a core-processing table.

Drill fluid and fluid handling

The type of drilling fluid to be used was a major consideration during the development of the DISC drill. The previous US deep drill had used *n*-butyl acetate as the drilling fluid; the fluid has a density very close to that needed to balance the glaciostatic pressure of the ice to keep the borehole open and stable. Concerns about the health issues presented by *n*-butyl acetate, however, led to survey study of possible drill fluids. The two-part fluid used by the European programs seemed the best existing alternative. That fluid uses Exxsol D-40, a de-aromatized hydrocarbon fluid used as a solvent in a number of applications, mixed with HCFC 141b, a halogenated hydrocarbon used as a cleaning solvent in the electronics industry, to produce the necessary density. After much consideration, it was decided to use HCFC 141b as the densifier for the West Antarctic Ice Sheet (WAIS) Divide Project and Isopar K as the base solvent. Isopar K is a highly refined, de-aromatized hydrocarbon that presents fewer health and safety concerns than~D-40.

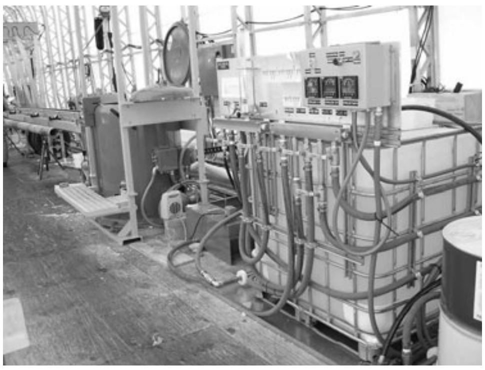

Fig. 11. Fluid-mixing tank in foreground, with centrifuge to the left.

The drill fluid is a solution of two compounds needed to be mixed for the correct density. The heart of the fluid-handling system is a mixing tank. All associated measurement devices, valves and pumps are integrated into the tank assembly and the mixing is controlled by a microprocessor (Fig. 11). The remainder of the system consists of the piping to transport the Isopar K and HCFC to the tank for mixing, and the piping to inject the mixture into the borehole. Fluid that drips from equipment and that is recovered from the ice chips is returned to the borehole. A centrifuge is used to remove fluid entrained in the recovered ice chips; the fluid is returned to the fluid system.

Screen cleaning

Screen-cleaning equipment (Fig. 12) includes a station where the screens are removed from the housing and the individual screen sections cleared of ice chips. The screen sections are reinserted into the housing at the screen-cleaning station. The screen-cleaning station is semi-automated. The chips are collected in a bucket inserted into the centrifuge for fluid removal.

Ancillary equipment

Equipment not directly involved with the drilling operation, but integral to the system, includes a shop facility and a gantry crane. The shop is contained in an expandable container shelter (Mobile Expandable Container Configuration (MECC^{TM})) manufactured by Weatherhaven (Burnaby, British Columbia, Canada) (Fig. 13); it consists of a machine shop, a welding shop and an electronics shop and is designed to facilitate the repair and modification of the drill equipment. The A-frame gantry crane has an 8 ton capacity and runs on rails that are also used by the smaller core-handling crane; the large crane is used to move equipment, particularly during drill-system installation and 'tear-down'.

Safety equipment

Safety equipment includes a multi-port gas monitor used to ascertain that areas exposed to drill fluid do not have dangerously high levels of vapors. Fire extinguishers,

https://doi.org/10.3189/172756407786857811 Published online by Cambridge University Press

Fig. 13. The MECC container that houses the shop; the sections to the right front and left rear collapse into the center section for shipping.

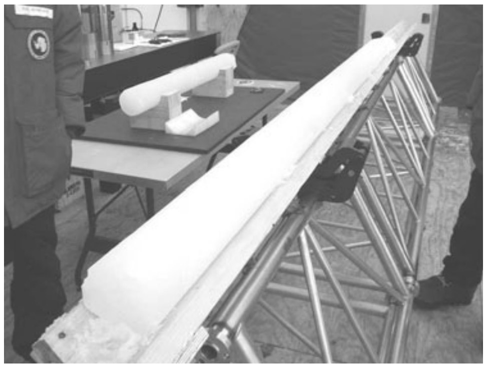

Fig. 14. A 2.7 m long core.

personal safety equipment and proper signage and alarms are also provided.

FIELD TESTING

The US science community and the NSF Office of Polar Programs (OPP) as well as ICDS believed very strongly that the DISC drill should be tested under field conditions before the system was deployed to Antarctica for the WAIS Divide Ice Core Project. A site at the Summit Camp in Greenland was chosen for the test. Scientists connected to the project and the OPP agreed that there should be no pressure to retrieve core to be used for scientific purposes; consequently, only a few of the ice cores retrieved were saved for analysis of drill performance.

The test of the DISC drill (Johnson and others, 2007) was conducted during the spring/summer of 2006, with site preparation, the drilling and casing of the pilot hole and installation of the large gantry crane occurring in the summer of 2005. The test had four major objectives: (1) to show that the drill system could be assembled, operated and disassembled safely; (2) to show that the drill could produce high-quality cores in both the ductile and brittle ice zones; (3) to show that the drill could gather, process and record critical science and drill data; and (4) to find weaknesses in the equipment and procedures that need to be corrected before the drill is deployed to WAIS Divide.

The field testing began in late April with the arrival at Summit of the first four members of the ICDS crew. The crew began the unpacking and assembly of the drill and were joined by several other crew members in early May. Installation and adjustment of the equipment was completed on 1 June when the first ice core was retrieved. The crew drilled a total of 666 m and reached a total depth of 766 m on 13 July when the coring was ended. The crew completed packing the drill system for shipment back to Madison on 20 July and finally left the camp on 25 July.

All major objectives were achieved. While there were a few mishaps, the drill was safely assembled, operated and disassembled. There were three minor injuries that resulted from unavoidable work conditions or carelessness. Three other incidents involved the failure of equipment, with the most serious being the knotting of the drill cable during a test of the winch capabilities after the last planned core had been retrieved. The addition of several alarms on the equipment will be necessary to prevent the recurrence of some safety issues.

Ice-core quality was deemed excellent in both the ductile and brittle zones; ice cores, in fact, were consistently excellent from the first core. ICDS had hoped that 4 m long cores could be retrieved consistently in ductile ice. However, core lengths averaged 2.5 m, with the longest being 3.1 m (Fig. 14). The length of the cores is limited by the amount of chips that can be retrieved, which, in turn appears to be a function of pump performance. Pump performance is expected to improve with the higher-density fluid at WAIS Divide (Isopar K was used without a densifier at Summit), but it is uncertain whether or not the 4 m core length can be achieved without a major design change.

The system was able, with a few exceptions, to collect the necessary drill and science data. Many of the data were 'noisy' due to electromagnetic interference in the sonde's electronic circuits, but the data were usable. The weight-on-bit sensor in the upper section of the drill sonde did not work properly and proved to be useless; the failure of the sensor was the primary reason for the 'knotting' of the cable.

Weaknesses in the system were found that should be corrected before the DISC drill is used at WAIS Divide. The electronic circuits will be modified to minimize noise, and the weight-on-bit sensor problem will be corrected. Several alarms will be added to the system to prevent accidents similar to those experienced. The winch level wind is of suspect reliability and durability and will be modified, and problems with leaks in sonde electrical connectors will be corrected. The winch gearbox is very inefficient and may be replaced to improve winch performance. A number of relatively minor modifications will also be made to improve the serviceability and ease of operation of the system.

FUTURE DEVELOPMENT OF THE DISC DRILL

Development of the DISC drill system will continue for the next several years. The modifications found to be needed after the test in Greenland will be completed before the drill is deployed to Antarctica for the WAIS Divide Ice Core Program in the late boreal summer of 2007. It is anticipated that a few additional modifications will be found to be necessary as the drill system is used for more extended periods and in different ice conditions. ICDS anticipates beginning the design and fabrication of drill system additions that will allow the sampling of the basal material at WAIS Divide, in 2008.

The DISC drill was designed with the concept of modifying it for use in 'replicate' coring through deviation drilling off the main borehole once the bottom of the ice sheet has been reached and the basal material sampled. While some very preliminary concepts for coring up to 15 m in a branch off the main borehole have been proposed, the selection of a method of accomplishing replicate coring has not yet been made. ICDS anticipates that it will begin this project in 2008.

ACKNOWLEDGEMENTS

During the 7 year course of the design, construction, testing and first field use of the DISC drill, ICDS has had the benefit of advice and assistance from many people, too many to mention, and we are grateful to them all. In partiular we thank the members of the Eustes committee, who wrote an initial survey of depp ice-core drilling for us; S. Johnsen, N. Gundestrup, S.B. Hansen, J.P. Steffenson and other members of the University of Copenhagen group who hosted several ICDS visitors and taught us a lot about ice-core drills; P. Talalay and others at the St Petersburg Mining Institute who were similarly hospiable and informative; the Institut Polaire Français–Emile Victor (IPEV) and Programma Nazionale de Ricerche in Antartide (ANRI), cooperators at Dome Concordia station, for providing on-site training with the EPICA drill to a senior ICDS engineer; the Alfred-Wegener-Institut für Polar- und Meeresforschung for accommodating another of our engineers for a season of EPICA drilling at Kohnen station, Dronning Maud Land; L. Augustin, Hansen, Johnsen. D. Pomraning, F. Wilhelms and M. Wumkes for participation in design review meetings; K. Taylor for guidance along the path toward the ultimate goal of best ice-core science; the Department of Geology and Geophysics, University of Wisconsin–Madison, for lending us the services of some expert technical help in our time of need; the wonderful people of Veco Polar Services for logistical support of the crucial field test at Summit, Greenland; Raytheon Polar SErvices Corporation for all the planning and constructon of the WAIS Divide site where the proof of the pudding will be; and the US National Science Foundation (NSF) Office of Polar Programs for making it all possible. This work was supported under NSF contract OPP-003289.

REFERENCES

Eustes, A.W., W.W. Fleckenstein, M. Beiriger and S.S. Eustes. 2001. *United States deep ice coring rig assessment; report to Ice Coring and Drilling Services*. Golden, CO, Colorado School of Mines.

Johnsen, S.J. *and 16 others*. 2007. The Hans Tausen drill: design, performance, further developments and some lessons learned. *Ann. Glaciol.,* **47**, 89–98.

Johnson, J.A. *and 7 others*. 2007. A new 122 mm electromechanical drill for deep ice-sheet coring (DISC): 5. Experience during Greenland field testing. *Ann. Glaciol.,* **47**, 54–60.

Kelley, J.J., K. Stanford, B. Koci, M. Wumkes and V. Zagorodnov. 1994. Ice coring and drilling technologies developed by the Polar Ice Coring Office. *Mem. Natl. Inst. Polar Res.,* **49**, Special Issue, 24–40.

Kudryashov, B.B. *and 9 others*. 2002. Deep ice coring at Vostok Station (East Antarctica) by an electromechanical drill. *Mem. Natl. Inst. Polar Res.,* **56**, Special Issue, 91–102.

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.