ISTUK

a deep ice core drill system

by

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Abstract: The ice core drill system used to core to bedrock at a depth of 2037.63 m near Dye-3 in South Greenland (65°11'N 43°49'W h=2490m) is described. The drill is designed to provide good core quality and to be easy to maintain in the field. It is a probe type system, with the drill suspended on a 6.4 mm cable. The drill consists of two parts. An antitorque section prevents rotation of the upper part, containing the motors and the electronics. During drilling, the ice chips, produced by the cutters, are sucked into the lower, rotating part of the drill. The chips are transported inside the drill to the surface, where the drill is clamped to a 6 m tower and tilted to a horizontal position for easy core removal and drill cleaning. The cutters work like a plane, which reduces the cutting power and provides stable penetration, essentially independent of the load on the cutters. The drill is powered by a rechargeable battery pack, and is controlled by a microprocessor in the drill. The length and weight of the drill are 11.5 m and 180 kg, respectively. The tower and the winch including an electro-hydraulic pumpstation and 2500 m of cable weigh 900 kg total. Core length is about 2.2 m per run, and the weekly production is 120 m of 10 cm diameter core at 2000 m depth. The core recovery is better than 99.9%. Close to bedrock the hole deviates 6 deg from the vertical, and the temperature is -13°C (-20°C at surface). The hole is filled with a mixture of JET A-1 and PCE. The liquid is cleaned by a down borehole filter unit. The hole diameter is maintained with a reamer.

INTRODUCTION

Previously, 2 deep (exceeding 1000 m) ice cores to bedrock existed. One from Camp Century (1966) in Northwest Greenland (Ueda, 1968), the other from Byrd Station (1968), Antarctica (Ueda, 1969). The drill used to recover these cores was lost in 1969 (Garfield, 1976), and no deep ice core drill was then available. There was an attempt to make an oil-rig type deep drill, the wire-line system (Hansen, 1976), but development of this drill was halted in 1978. In recent years, a thermal drill capable of operating in liquid filled holes has been made in the USSR (Zotikov, 1979), however the operating principles of this drill (thermal drilling in ethanol) limit the applicability of the core for analysis.

ISTUK SYSTEM

The objective was to develop a drill capable of penetrating the Greenland Ice Sheet to a depth of 3300 m at temperatures down to -32°C. The temperature of the ice would be so low that no melting occurs. The core quality should be as good as possible. In addition, the drill should be so easy to operate that inexperienced students could serve as operators. Thermal drilling was excluded because stress created by the thermal shock causes breaks in the core. Furthermore, a thermal drill consumes about 5 kW of power (Mellor, 1976), and transport of this amount of energy to a drill 3300 m downhole is difficult.

Two different mechanical systems were considered: the oil-rig type and the probe type with the drill suspended on a cable. It was decided to use the probe system for several reasons, mainly due to lower costs and the ease of making modifications in the field. Also, the cuttings had to be removed in order to allow drill penetration. In the drill used at Camp Century and Byrd Station, the cuttings were dissolved in glycol. This system is complicated, and therefore it was decided to remove the chips by pumping the cuttings directly into storage chambers in the drill.

The drill is powered through the drill cable using a battery in the drill as a buffer. Thus the average power consumption and not the peak power could be used in designing the drill cable. This reduces the cable dimensions by a factor of 10, because the drilling time is just 6 minutes compared to a typical run time of 1 hour, and the rest of the run time is spent in hole transit and maintenance at the surface.

In fact, this concept is so effective that power transfer capacity is second to mechanical strength in specifying the cable. A 6.4 mm cable can power a drill 3300 m downhole!

The drill is controlled from the surface, and it is considered important to transmit as much information as possible regarding the drill behavior from the drill to the operator. Production of perfect ice cores is not easy due to greatly varying pressure, temperature, crystal size and orientation. In order to handle this, the drill was considered an instrument designed to produce ice cores, and not just a tool to generate cuttings. Following this philosophy, one microprocessor was used in the drill, and another one at the surface. In this way, the operator was relieved from most trivial tasks, and could concentrate on the winch and high level drill control. As a consequence, an operator can be trained in just 3 days. In addition, the computers enhance the reliability of the operation. If the down borehole computer detects an abnormal condition that may endanger the drill, it unconditionally shuts the drill down and notifies the operator. After removing the error condition, the drilling continues.

The drill tower is a blown-up version of the hinged tower used in the Danish shallow drill (Johnsen, 1980). The idea is to tilt the drill when it is clamped to the tower. This brings the drill to a horizontal position at the surface for easy core removal and drill maintenance. In addition, the tower height is reduced to 6 m, or about half the length of the drill.

The drilling proceeds in 'runs', and every run consists of the following steps. First, the drill is lowered down the hole. When the drill touches the bottom, the lower part of the drill rotates, cutting away a ring of ice. The produced chips are sucked into storage chambers inside the drill. After drilling about 2.2 m of core, the rotation is terminated and a pull in the cable makes the core catchers break the core. The drill with ice core and chips is hoisted to the surface. After cleaning, the cycle is repeated. At a depth of 2000 m, one run takes close to 2 hours.

The upper part of the hole was cased by U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), using 10-ft. long steel tubes with an inner diameter of 178 mm (Rand, 1980b). In order to counteract the hydrostatic pressure of the ice, the hole was filled with a mixture of kerosene (Jet A1) and perchlorethylene (PCE).

Drill

The drill is sketched in Figure 1. The length of the drill is 11.5 m, and it cuts a hole with a diameter of 129.5 mm. The core diameter is 102.3 mm. The ice is cut with a plane-like system consisting of 3 aggressive knives backed by stopper shoes controlling the pitch. The produced chips are mixed with hole liquid and sucked into 3 channels on the outside of the drill. Each channel ends in a piston pump acting in a storage chamber.

The upper part of the drill, including the antitorque system, pressure chamber with motors, and a screw at the lower end of the pressure chamber, is prevented from rotating by 3 leaf springs pressed against the hole wall. The cable is terminated with ball bearings in a weight inside the antitorque system to allow for rotation of the cable. The weight serves as a hammer, which can be used to break the core.

The drill has 3 independent piston pumps, one for each cutter. The pumping action is created during gradual changing of the distance between a disc clamped to the rotating tube and another clamped to a center shaft which is connected to the motor section. In fig. 1, the shaded parts are connected to the motor exit shaft. The motor rotations are transferred to the lower part of the drill, the drill barrel, through a hollow screw, a triangular shaft and a linear bearing. The roller nut on top of the barrel engages the external thread on the screw and creates a linear motion of the barrel. This changes the distance between the discs and creates the pumping action. The diameter of the pump is 100 mm which gives an effective volume of 7 l per chamber. With a core length of 2.3 m, the volume of the ice cut by each cutter is 3.8 l. The pitch of the screw is 4 mm, and the number of rotations is 234, giving a stroke length of 936 mm.

The triangle- and piston-section are connected with a 4 mm pin which protect the piston section in case of overload.

A position-operated ball valve has a dual function. When the chip chambers are at minimum volume before the start of drilling the ball valve vents the chamber. When the drill moves up after drilling, released air from the cuttings is vented through the same valve. A second ball valve acts as a safety valve. The released air cannot escape through the channel due to a flap valve at the inlet between the channel and the chamber (not shown on the figure). This valve prevents loss of chips through the channel.

The core chamber has an inner diameter of 104 mm and a length of 2.95 m, including the drill head. The maximum possible core length is 2.75 m. A filter in the upper part of the chamber collects ice chips floating in the hole liquid while lowering the drill down hole.

Drill head

A stable drill head was manufactured from a single piece of steel using the spark erosion technique. On the drill head (fig. 2), a total of 18 components are mounted, including: 3 cutters, 3 shoes, 3 channels, 3 core dogs and 6 leaf springs. The ice chips move up in front of the cutter, and are mixed with hole liquid and sucked into the channels. The leaf springs keep the cutters away from the joints in the casing.

The core catchers are dog-leg shaped. They are spring-loaded against the ice core. They are so

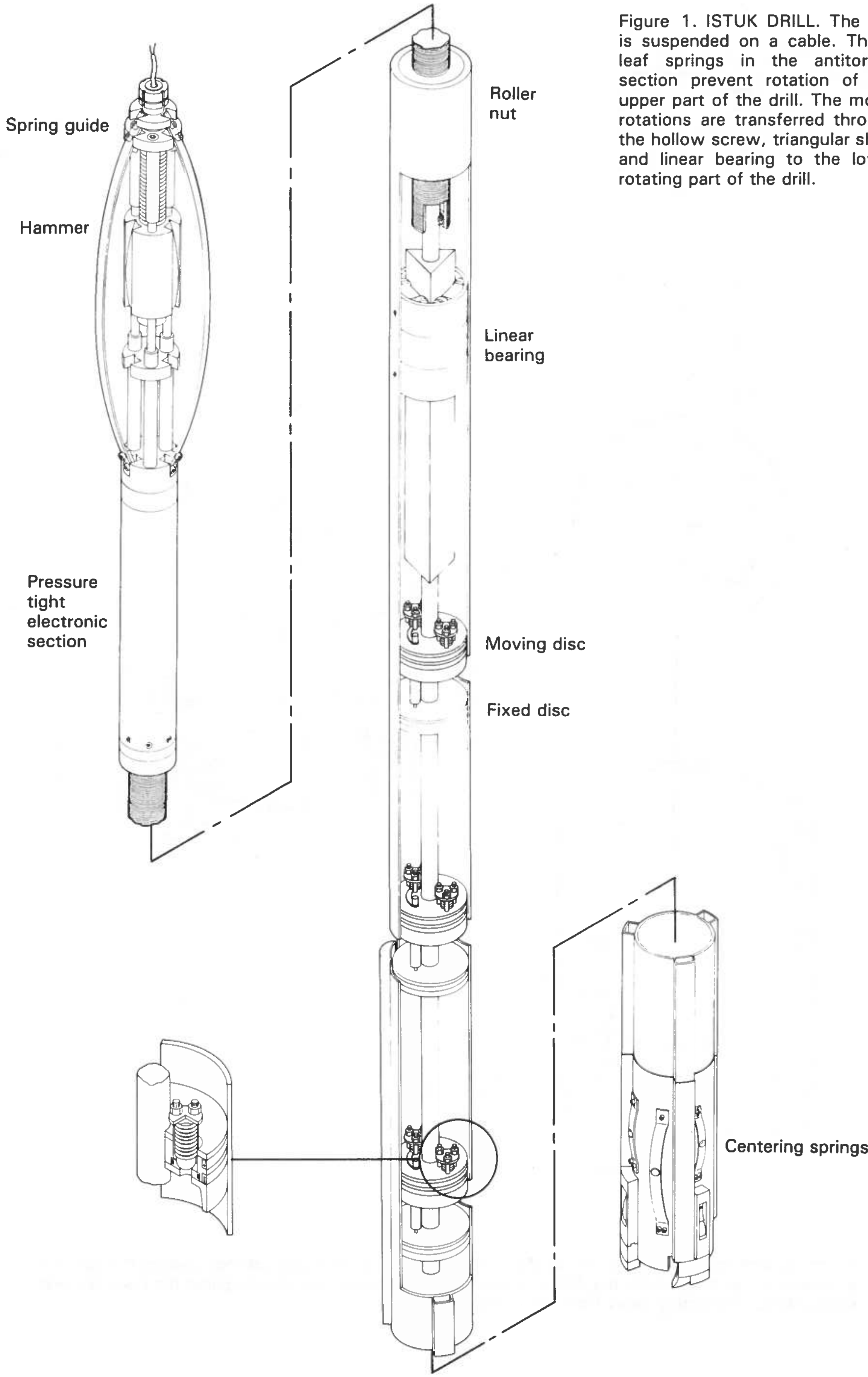

Figure 1. ISTUK DRILL. The drill is suspended on a cable. The 3 leaf springs in the antitorque section prevent rotation of the upper part of the drill. The motor rotations are transferred through the hollow screw, triangular shaft and linear bearing to the lower rotating part of the drill.

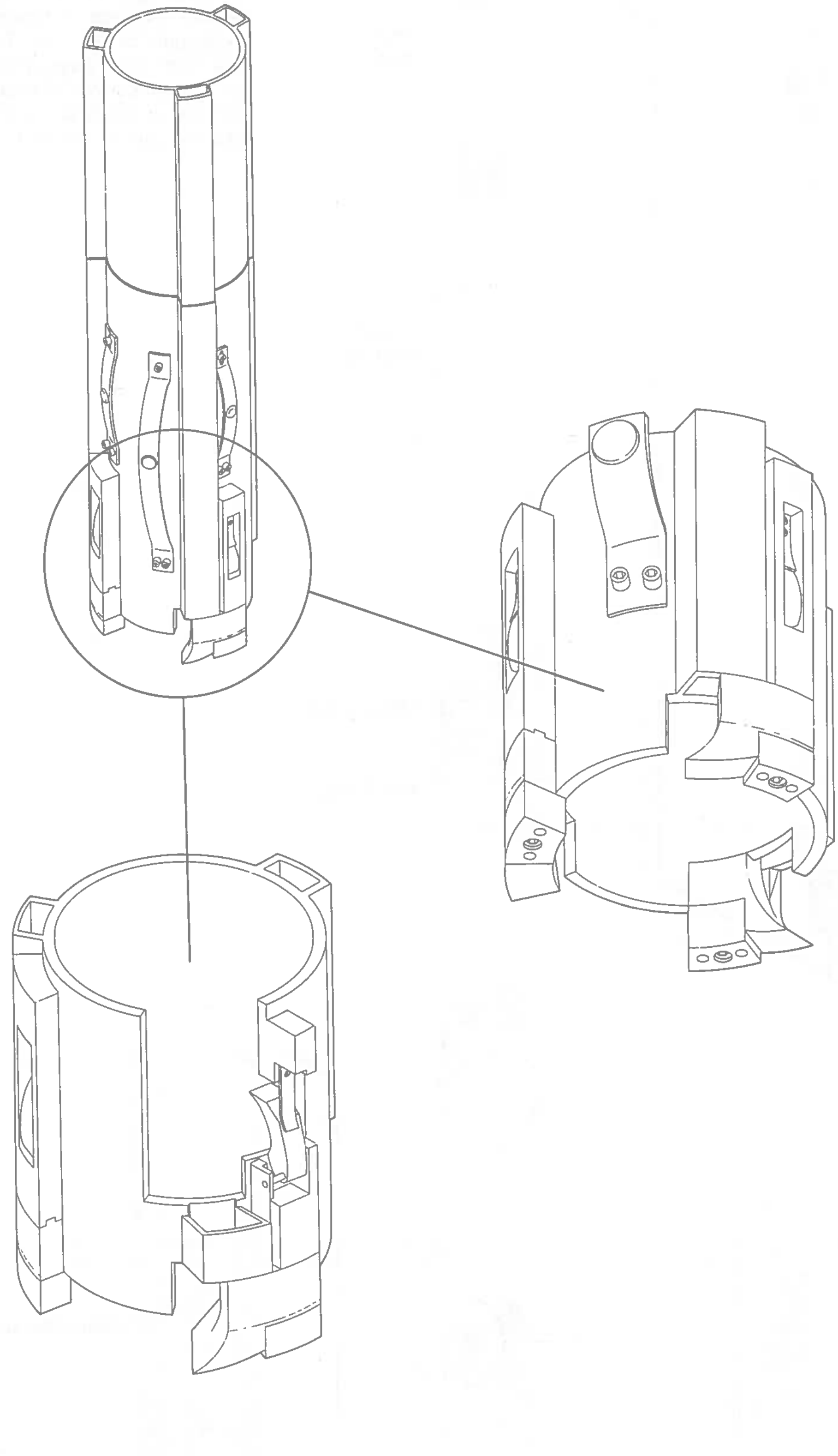

Figure 2. Drill head. The ice is cut by the 3 knives, and the produced cuttings sucked through the channels to chambers inside the drill. The core catchers are spring-loaded against the core. Six leaf springs keep the cutters away from the casing.

aggressive that they always worked. During the major part of the drilling, just two core catchers were used. The asymmetrical stress caused by two core catchers made the break easier than if three core catchers had been used. The natural position of the core catchers is the horizontal position. But the core catchers should have been spring loaded to ensure the upright position as the natural one. We found that if the core break left a slanted surface on the remaining core, then the core catchers would turn into the side of this surface when the drill started to rotate in the next run. The skew side then would break with a high probability of a lost run.

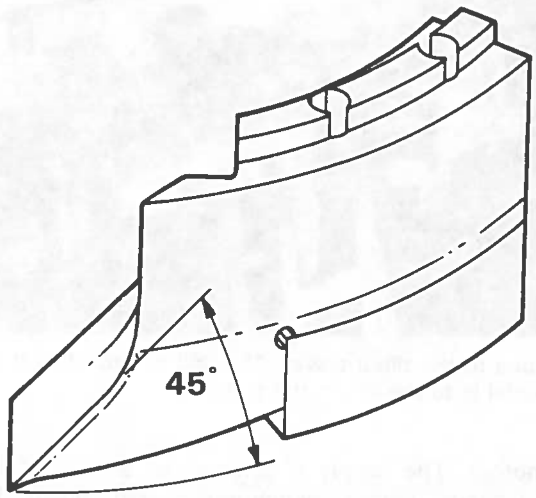

Figure 3. Cutter. The cutter works like a plane with the pitch controlled by a shoe behind the cutter.

Cutter

Each of three cutters (fig. 3) is mounted on the drill using a keyway and two screws. This mounting method is very rigid and ensures a constant core diameter of 102.35 mm. The front of the cutter is shaped to guide the chips into the channel. There is a 8.6 deg clearance angle between the cutter and the ice, and the forward cutting angle is 45 deg. With a pitch of 1.4 deg, the remaining 35 deg for the cutter is about the minimum due to mechanical reasons. All cutting edges, including those on the sides of the cutter, have a relief angle which reduces the power required to turn the bit and produces stable drilling characteristics. The shoe determines the pitch. These angles are not special for this drill, but are considered common to all electromechanical ice core drills used in cold ice. A plane cutting system does not require different cutters due to changes in ice conditions. By changing the 'shoe size', core length can be varied.

Pressure Chamber

All down borehole electronics, including motor and gear, are contained inside a pressure-tight steel tube with an inner diameter of 100 mm. The tube is tested to withstand a pressure of 400 bars. Any leakage through the high pressure sealings is trapped in volumes between the high-pressure sealings and low-pressure O-rings. The pressure in these volumes is monitored by pressure transducers. In order to facilitate easy maintenance in the field, the electronics are constructed as stackable cylindrical modules. The modules, with plugs at both ends, fit together and a key ensures the modules are connected in the correct order. A total of four modules (power supply, computer, battery and motor power supply) are mounted on top of the motors, and a rubber spring between the upper module and the top pressure tube cover keeps the modules together.

Computer

The purpose of the down borehole computer is to monitor and control the drill operations. This includes charging and discharging the battery, keeping the battery temperature close to 20°C, monitoring four pressure transducers for any sign of leakage or outgassing of the battery, monitoring inclinometers for loss of antitorque, etc. A total of 30 analog parameters are measured. All measured values are compared to a limit. If this limit is exceeded, the computer takes appropriate action, and if it is a condition that may endanger the drill, the computer unconditionally shuts down the drill. After removal of the error condition, the drilling can continue. The drill communicates with the surface terminal using 300 Baud full duplex CCITT compatible audio tones riding on top of the supply current to the drill. Thus, just a single conductor coaxial drill cable is needed, and a commercial converter between the audio tones and digital signals (modem) can be used at the surface. The computer receives commands from the operator regarding drill speed, direction, etc., and transmits to the surface information on status, cutter load, motor current, battery current and screw position in addition to 27 other parameters.

Battery section

The major part of the energy required for the actual drilling is delivered by the battery pack. This consists of 55 pcs of 2 Ah 'SAFT' commercial C-size Ni-Cd cells heated to 20°C. The discharge current is about 7 A corresponding to a charge consumption of 0.75 Ah for a run. With a load current of 7 A, the capacity of the cells is at least 1.5 Ah.

Under normal use, the lifetime of a Ni-Cd battery is specified to 100 cycles. Hodge (1976) points out that the battery lifetime may in fact be several thousand charge-discharge cycles if the following conditions are observed: The battery temperature is kept close to 20°C, the battery is not too deeply discharged, the charging current for a 2 Ah cell is between 1 amp and 4 amp and the battery is never overcharged. The first 3 conditions are easy to fulfill, and overcharging is prevented by using

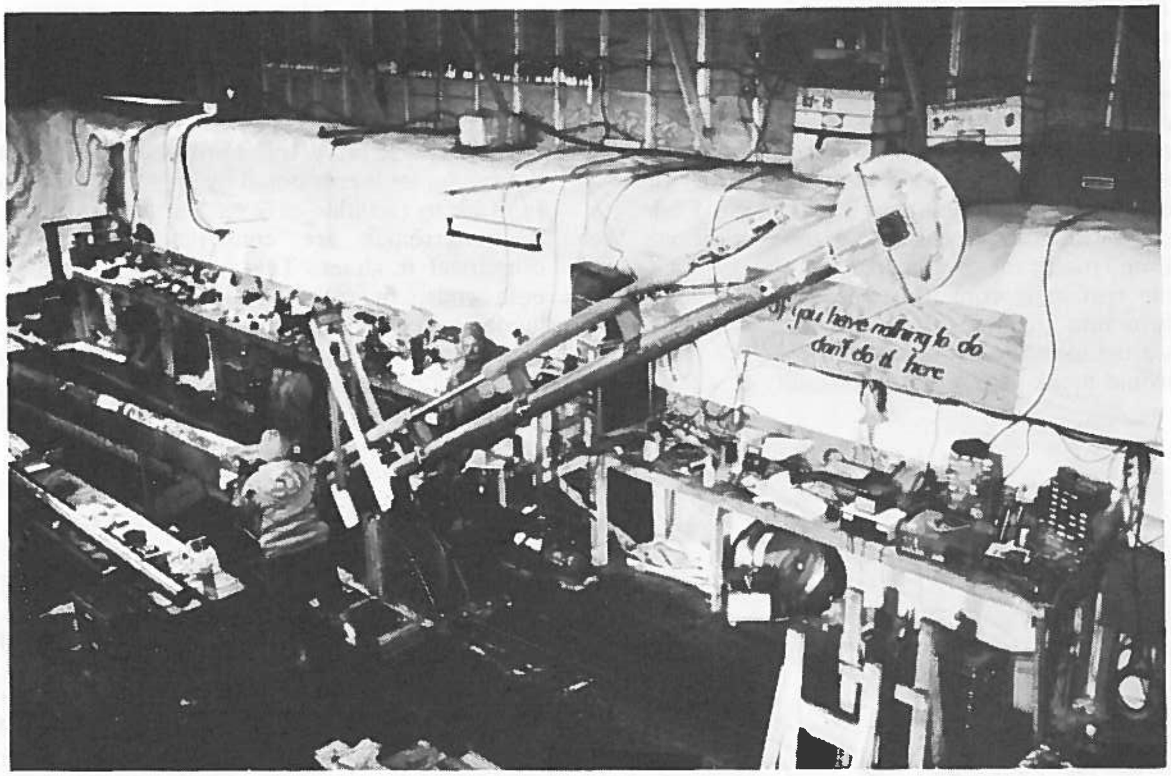

Figure 4. Drill shelter. The picture shows the drill clamped to the tilted tower. The drill is moved to the upright position for rewinding the screw. A spare drill barrel is to the left in the picture.

battery temperature, current and voltage to indicate the level of charge. Thus the down borehole microprocessor terminates the charge at the correct time based on the empirical equation valid for this cell:

$$V = 1.54 - T * 0.003 + I * 0.015$$

V is cut-off voltage per cell in Volt
T is battery temperature in Celcius.
I is charge current in Ampere

This method is so effective that no battery failures occured, nor did any sign of outgassing or battery deterioration take place (Klipstein, 1967).

The battery pack consists of 5 columns, each containing 11 batteries. A heavy copper foil is wrapped around the 5 cylinders to keep all cells at the same temperature. Two wire heaters are in thermal contact with the copper foil, and about 8 mm of insulating foam is moulded to the outside. The power required to heat the battery section from -20°C to +20°C is 25 W.

Motor Power Supply

The motor power supply converts the battery voltage (55 V to 85 V) to a variable voltage for the motors. Nominal output voltage is 48.5 V. This can be changed by the computer to 10.5 V, 38 V or the battery voltage. The polarity of the voltage can be reversed. The maximum output current is limited to 12 A, thereby limiting the maximum torque of the motors. The supply is constructed as a very high efficiency (94%) switch-mode step down DC supply.

Motor-gear section

The drill motor is a low-temperature lubricated dual disc type DC motor (Mavilor type 81). The motor efficiency is 75%. On the shaft of the motor is mounted the Harmonic Drive gear (type 20-160-2A), which reduces the nominal 6000 rpm of the motor to 37,5 rpm in one step. Considering that the required lifetime of the gear during drilling is just 200 hours, the gear is lubricated with a low viscosity 10 cSt silicone oil, (Dow Corning Fluid type 200) which ensures high efficency operation of the gear. Fine molybdenum disulphide powder added to the gear oil ensures sufficient lubrication. The number of rotations is limited by the screw to 234, corresponding to a drilling time of 6 min 15 sec with the nominal rotation speed of the motor. A shaft encoder is mounted on the motor. By counting motor revolutions, the computer calculates the screw position.

Below the gear, a ball-bearing section absorbs the static pressure on the exit shaft as well as the force created during core-break. This section is designed to withstand the cable breaking force of 25 kN.

If the screw should be blocked, the motor-gear section is protected against overtorque by a 6 mm pin which connecs the exit shaft to the triangle section.

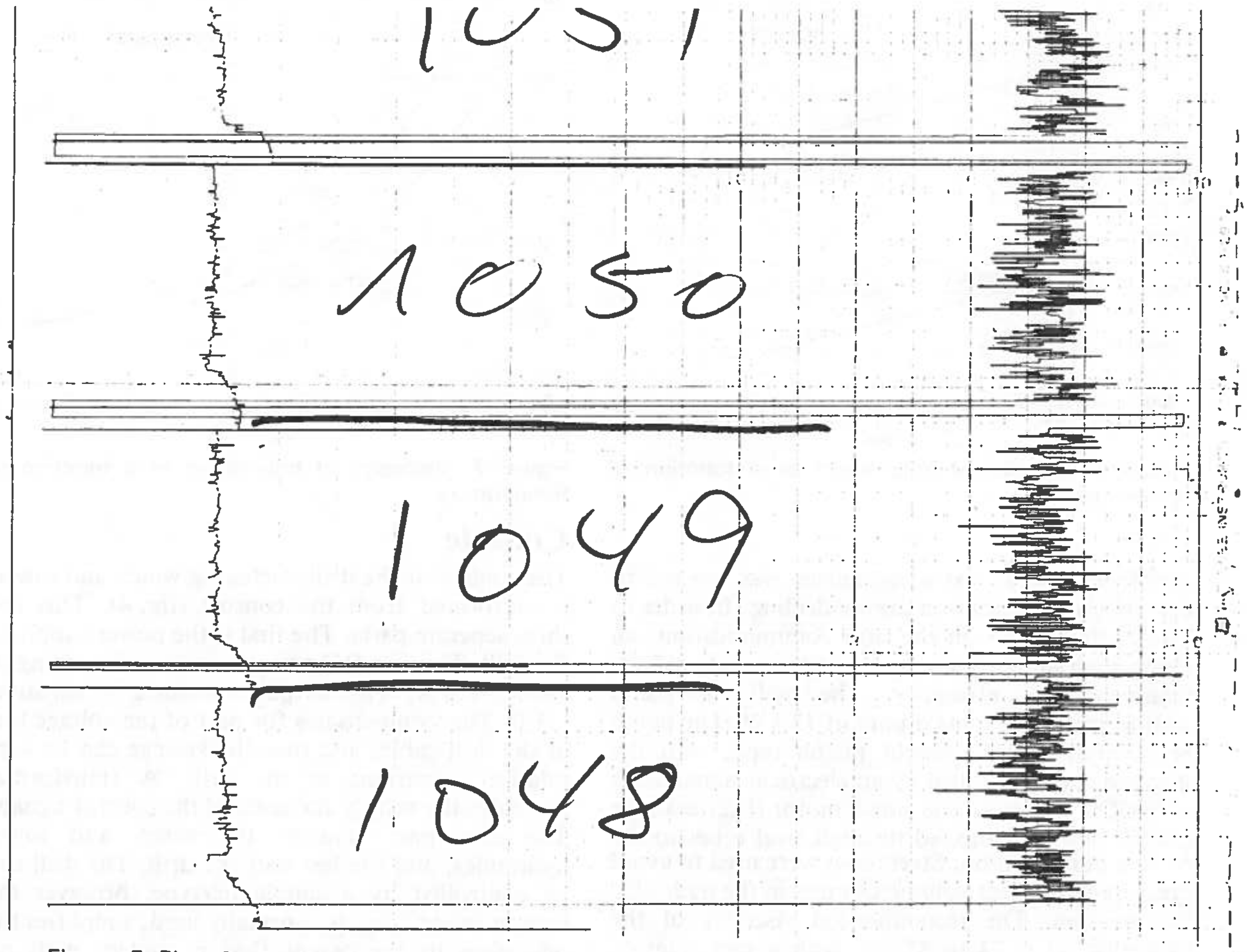

Figure 5. Plot of cutter load (left) and motor current (right) for some runs. The motor current is unaffected by cutterload.

Antitorque section

The purpose of the antitorque section (fig. 1) is to prevent the upper part of the drill from rotating relative to the hole wall, and at the same time to allow for vertical movement of the drill with minimal friction against the hole wall. The system is similar to that used in our shallow drill. Three leaf springs, spaced symmetrically around the drill axis, prevent the rotation. The springs are 2,5 mm thick, 20 mm wide and the distance between the supports is 690 mm. They are bent in a fourth-order parabolic shape in order to ensure a uniform load distribution along the 355 mm length of the spring in contact with the hole wall. The nominal radial force for each spring is 390 N, corresponding to a maximum bending stress in the spring of 760 MPa. The total antitorque section can produce a torque of 100 mN when the edges of the springs are sharpened.

The distance between the supports for the leaf springs can be adjusted by moving the upper support. A guide close to this support prevents rotation of the springs. This antitorque system is very simple, compact and rugged. Calculations for the springs are shown by (Reeh, 1982).

The cable, which is mounted in a steel hammer surrounded by the leaf springs, is attached in such a way that it allows the cable to rotate relative to the drill. The hammer can move 10 cm along the drill axis. The cutterload is determined by a spring on the upper 2.5 cm of this distance which combined with a linear transducer, measures the position of the hammer.

Cable

The cable is Rochester type 4H-252K. This is a steel-armored 4-conductor teflon-insulated cable. The diameter is 6.45 mm and the breaking strength is 24950 N. Weight in air is 153 kg/km. The resistance of the shield is 11.5 Ω/km, and the four conductors operated in parallel have a resistance of 16.7 Ω/km. The maximum voltage is 300 V DC. The maximum applied voltage is 200 V.

Winch

Winch requirements were for a nominal cable speed of ±1 m/s and a minimum speed of a few cm/s. The depth position of the cable in the hole should be controllable to within a few cm. With these

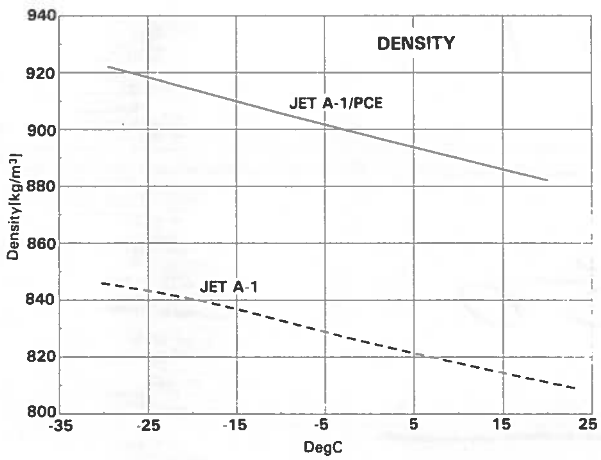

Figure 6. Density of hole liquid as a function of temperature.

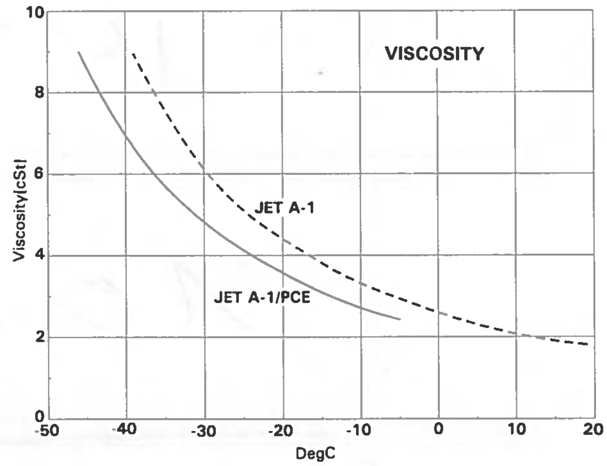

Figure 7. Viscosity of hole liquid as a function of temperature.

specifications, no extra mecanism was needed to control the drill position during drilling. In order to avoid interference on the drill communication, an electrohydraulic winch was used is spite of its relatively poor efficiency. The hydraulic pump station consumed a maximum of 13 kW. The pump is a variable displacement piston type, with the displacement controlled by an electrical signal using a 'MOOG'-control. The winch motor (Danfoss type OMSS-160) is connected through steel tubes to the remote pump station. Steel tubes were used to avoid pressure-dependent volume changes in the hydraulic transmission. The recommended viscosity of the hydraulic oil is 73 to 37 cSt, with a minimum of 21 cSt. The oil is Mobil type Aero HFA. The same oil type was used in the Byrd Station drilling. Although this oil has very little change in viscosity with temperature, the viscosity was frequently less than 21 cSt, corresponding to an oil temperature higher than 24°C. The winch drum holds a maximum of 3500 m of 6.45 mm cable. The cable is positioned on the Lebus grooved drum by a guide wheel.

The maxium force from the winch is limited by an overpressure valve in the hydraulics to 8 kN, compared to a cable breaking force of 25 kN. This means that the winch is not able to break the cable even when operating the hammer in the drill. The absence or release of pressure on the hydraulic locks the winch.

Tower

The tower is hinged and can be tilted by a hydraulic piston. The piston is controlled by a small hydraulic pump through a proportional valve, allowing a variable tower speed.

The tower and winch are bolted to the ends of two 10*6-inch timbers, 25-ft long which are spaced 3-ft apart.

Console

The control of the drill, including winch and tower, is performed from the console (fig. 4). This has three seperate parts. The first is the power supply to the drill. This is a DC power supply with a rating of 190 V, 2.8 A. The output resistance is negative, -33 Ω. This compensates for part of the voltage loss in the drill cable, and thus the voltage can be kept relatively constant at the drill. A transformer separates the supply current and the control signals. The next part controls the winch and tower hydraulics, and the last part the drill. The drill can be controlled by a simple teletype, however the computerized console, normally used, simplifies the operation to the extent that a student with no previous knowledge of the system, could learn to operate the drill after a few days. The computer used is an ABC-80, a relatively fast personal computer. It is interfaced to the depth counter, the drill modem, a dual channel analog strip chart recorder for recording cutterload and motor current, a digital printer and a TV monitor. The computer transforms the drill information, and provides a semi-analog display of motor current, cutter load and screw length on the screen, and tables showing 30 other parameters, i.e., drill penetration during a run, temperature, inclination etc. The operator controls the winch based on this information. Fig. 5 is a plot of cutter load and motor current for some runs. The cutter load decreases after the start of drilling, and then remains constant because the operator gives slack in the cable. The motor current is not influenced by the cutter load. This is typical for a plane-like cutter system. A constant motor current during a complete run indicates that there is no sticking between the core and barrel, and that the pumps are working correctly. In fact, the cutter load is negative because after the start of drilling, we pull in the cable to obtain a negative cutter load of about 500 N. Due to the aggressive cutters, this negative cutter load has no influence on the pitch and thereby the core length. The negative cutter load stabilizes and minimizes the drill inclination.

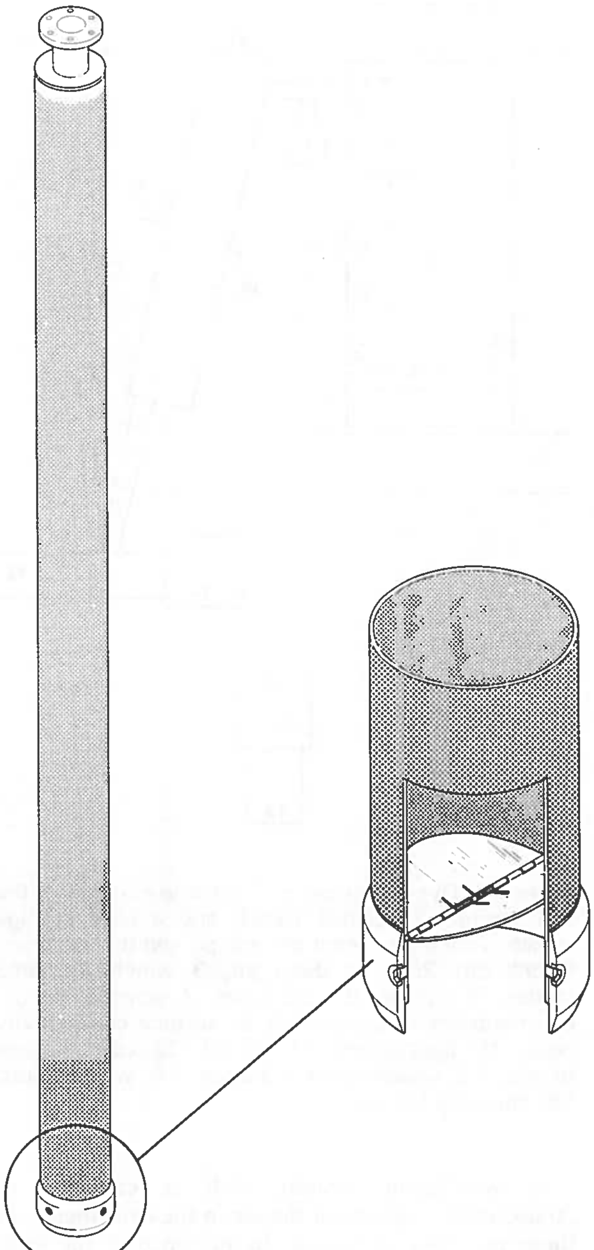

Figure 8. Downbore hole filter. The spring-loaded valves at the bottom of the filter (lower right) open when the filter moves through the hole liquid, collecting the floating chips.

Hole liquid

In order to compensate for the hydrostatic pressure of the overburden ice, the hole is filled with a liquid. This liquid should not react with the ice, the density must be close to 920 kg/m^3, and the viscosity not so high that the winch speed is adversely affected. In the Byrd Station drilling, a mixture of kerosene (DF-A) and trichlorethylene was used. At Dye-3, Jet A-1 was used due to its specified viscosity at -20°C (Table 1) and its higher purity. However, the difference between the two fluids is small.

TABLE 1. Hole liquids

Proporties	DF-A	JET A-1
Density (15°C)[kg/m^3]	770-840	775-830
Viscosity [cSt]	1.4-2.5/38°C	max 8/-20°C
Vapour Pressure [mmHg]		max 0.4/10°C
Freezing Point [°C] max	-48	-50
Flash Point [°C] min	40	38

TABLE 2. Density adjusters

Proporties	Trichlor	Perchlor
Density [kg/m^3]	1470	1620
Freezing Point [°C]	-86	-23
Vapour Pressure [mmHg]	56/20°C	14/22°C
Flash Point [°C]	32	not flammable
Boiling Point [°C]	87	121

The density of the hole liquid was increased by the addition of 10% Perchlorethylene (PCE) to the kerosene. PCE was preferred over trichlorethylene because it is less toxic due to a 4-times lower vapour pressure. Furthermore, PCE cannot burn, and has even been used as a fire extinguishing agent. PCE freezes at -23°C, but that is no problem in Greenland during the summer. Both kerosene and PCE are very aggressive solvents. Thus, all gaskets must be either Teflon or Viton.

As shown in fig. 6, the density of the liquid varies with temperature. This must be corrected for when mixing the liquid. The casing leaked at the bottom, so in order to compensate for the missing 50m of liquid, the density of the hole liquid was increased to 950 kg/m^3. The PCE freezing point of -23°C does not influence the mixture (fig. 7), so that could be used down to -50°C.

Filter

Not all of the cuttings are collected in the drill, and some ice is scraped from the hole wall by the cutters during hole transit. These chips were collected twice a week by a down borehole filter (fig. 8). The filter is bolted to the bottom of the electronics section after the screw and barrel are removed. When the filter passes down through the liquid, the spring loaded valves at the botton open, and the chips are collected in the filter. As the density of the hole liquid is higher than that of ice, the chips float upwards in the hole, and just the upper few hundred meters of the hole have to be filtered. The high density also keeps the bottom of the hole clean. For these reasons, it is advantageous to use a hole liquid with a sligthly higher density than the ice.

Reamer

The Dye-3 drilling was a multiseason operation, with 9 months between the field seasons. During this time interval, the hole had a tendency to close

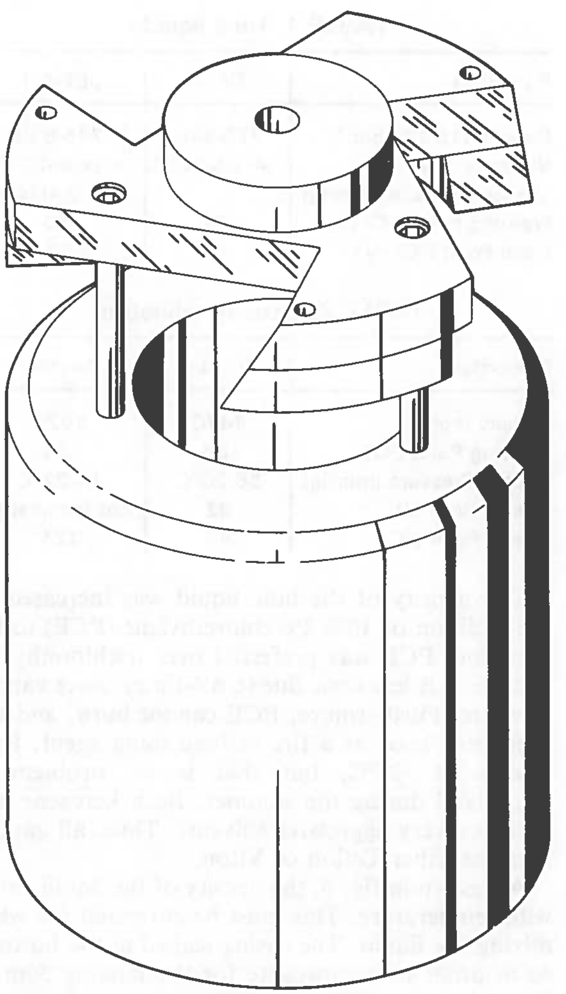

Figure 9. Reamer. The reamer is mounted on the exit shaft of the electronic section. The front cylinder centers the unit in the hole.

due to the missing 50 m of liquid. Although the change in hole diameter was small (Johnsen, 1980), any change could have stuck the drill. Therefore, the nominal diameter was increased from 129.5 mm to 130 mm before drilling resumed each season. A simple reamer (fig. 9) was used. It is mounted directly on the exit shaft of the electronic section. The front cylinder centers the reamer in the hole. During 1981, an improved version that could be bolted directly to the motor section was used.

Camp

The drilling took place inside a 24.4 m by 9.8 m shelter in a 18 by 6.7 m pit, 4 m below the original surface (fig. 10). This pit was connected by a tunnel to the science trench where numerous investigations were conducted continuously on the cores. Another tunnel connected the science trench and the core storage trench. A cold cave between the drill pit and science trench stored 40 m of core. Cores from the brittle zone (700-1400m) were stored 2 days prior to handling to reduce their fragility.

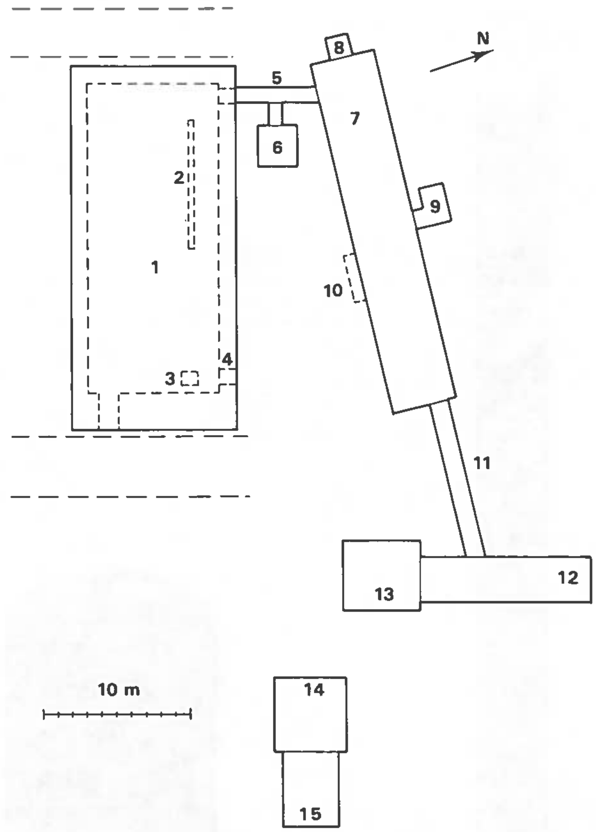

Figure 10. Dye-3 drill camp. The camp consists of the drill shelter, a science trench and a core storage trench. Tunnels connect the drill pit and the trenches. 1. drill pit, 2. 6 m deep pit, 3. winch, 4. pump station, 5. tunnel, 6. cold cave, 7. science trench, 8. emergency escape hatch, 9. surface conductivity cave, 10. dust room, 11. tunnel, 12. core storage trench, 13. weatherport entrance, 14. weatherport, 15. chemical lab-van.

A ventilation system with a capacity of 20,000 m^3/h exchanged the air in the drill shelter 10 times per hour to reduce the presence of the toxic fumes from the hole liquid.

Results

The idea of making a new drill was first raised in the autumn of 1977. The basic principles of the drill were tested at Dye-3 in the summer of 1978, and the prototype was tested at CRREL in the spring of 1979 (Rand, 1980a). In 1979, a casing was installed by CRREL at Dye-3 (Rand, 1980b), and later the prototype drilled to 225 m. The core production was limited by weaknesses in the drill that were ageravated by rust particles from the casing. In 1980 the drill was improved, but a breakdown terminated the season at 901 m. In 1981, drilling started with run 755 and continued smoothly after the intial adjustments (fig. 11). The core production rate was 120m/week which is the same as for the Byrd Station drilling program. The termination of the

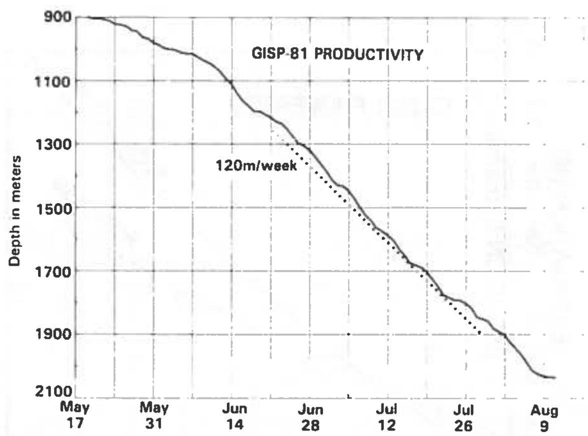

Figure 11. GISP 1981 production versus depth

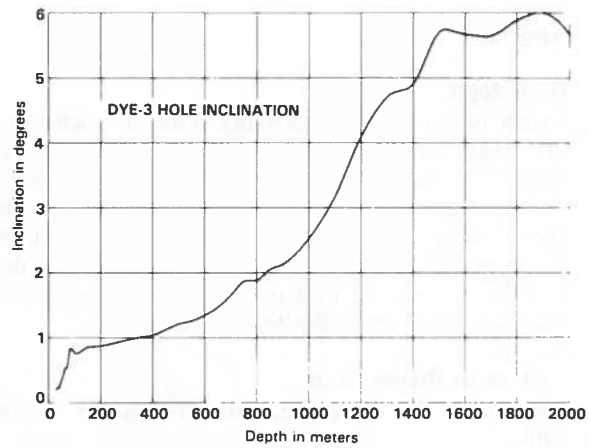

Figure 12. Inclination of the drill hole. Azimuth is not known.

last glaciation was found in run 1285 at a depth of 1786.80m. The first indication of bottom material was found in run 1371 at a depth of 1949.45 m. Silty ice started in run 1400 at 2012.83 m. The final depth was 2037.63 m in run 1418 when the drill was stuck. The drill was left with tension in the cable and excess pressure in the hole during winter. By the summer of 1982, the drill had become loose, and after being raised to the surface, the last core was removed from it. The drill itself was undamaged. 500 ml of the hole liquid had seeped into the pressure tight section.

The ice core by this drill is is of excellent quality, and no part of the core is known to be missing. It is estimated that less than 2 m of core was lost, resulting in a core recovery of better than 99.9%. The brittle zone (the depth at which the core becomes brittle at the surface) was 700 m to 1400 m which compares with 400 m to 900 m at Byrd Station (Ueda, 1969).

The specific energy, that which is used to produce $1 m^3$ of cuttings, increased with depth in spite of improvements in the cutting system. Close to the hole bottom the specific energy was about $16 MJ/m^3$. This increase agrees with an estimated increase in fracture stress with pressure (Shoji, 1978). Ice from the ice age shows a marked reduction of viscosity (Shoji, private communication), however this does not change the specific energy.

A cable-suspended drill tends to deviate from the vertical as it penetrates. Fig. 12 shows the hole inclination with depth. At a depth of 1400 m, modifications to the cutters stabilized the inclination at 6 deg compared to 15 deg at the bottom of the Byrd Station borehole (Ueda, 1969). The azimuth is not known.

The ice temperature close to surface was -20°C, and at the bottom, the transducers inside the drill measured the temperature at -12°C in 1981. In 1982 the hole temperature close to the bottom was measured at -13.40°C using a calibrated thermistor. The reason for this change is not yet known.

Conclusion

A new deep ice core drill for cold ice has been developed. It has a demonstrated capability of drilling a 2 km ice core, and the same principles can be used to a depth of 3.3 km. The basic concept of the instrumented drill, i.e., the battery section, the replacement of mechanics with electronics, the in-principle simple mechanics, worked as anticipated. There is no indication that we are close to a limit of the system; a longer drill would be able to take longer cores thereby increasing the penetration rate, and the system could be made to work with minor modifications to the electronics, in very cold ice. The penetration rate is 120m/week. The drill is easy to maintain in the field. The ice core is continuous and of good quality. Due to the use of a microprocessor in the drill, an operator can be trained in just 3 days.

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Appendix

Hole depth

Depth measurement is usually done by measuring the length of the retrieved core. In a multiseason operation vertical strain makes the corelength shorter than the actual depth of the hole. In the Dye-3 deep drilling, all depths are given as accumulated core length with reference to the june 8, 1979 surface. At that date, the following depths were measured from the reference surface:

4.0 m to shelter floor
10.5 m to top of casing, which is bottom of drill pit
68.5 m to top of thermodrilled hole inside casing
81.7 m to bottom of thermohole, start of ISTUK drilling.

The bottom of the casing was at 76 m (Rand 1980b). In 1980, the casing had moved 30 cm up relative to the bottom of the drill pit. This indicates, that the casing followed the ice movement of the 68 m layer where the casing was fixed to the ice by the frozen water. The 30 cm movement is in accordance with the difference in annual ice thickness of 92 and 60 cm at the depths of 10.5 and 68 m respectively. In order to ensure clearance, the upper 89 cm of the casing was removed in 1981. In 1982, PICO added 45 ft. of casing.

The amount of core retrieved was measured by placing the cores on high quality graph paper, and fitting the cores together. Due to deficiencies in this procedure in 1979, the actual hole length may be up to 65 cm more than indicated. In the following years, starting from a depth of 224 m, the procedure was improved.

Drill Cable

The manufacturer performed the following measurements prior to delivery:

1. Diameter measured under light tension every 300 m varies from 6.38 mm to 6.40 mm.
2. DC conductor resistance is 15.75Ω/1000m, all 4 conductors in parallel.
3. Capacitance is 148 pF/m, one conductor to all other and armor together.
4. Breaking strength: 28.5 kN, ends fixed, 23.6 kN with one end free to rotate.
5. Breakdown voltage with cable bent over 10 inch diameter sheave: 10 kVAC was applied between conductor and armor and no breakdown occured.
6. Elongation and rotation, see fig. 13.

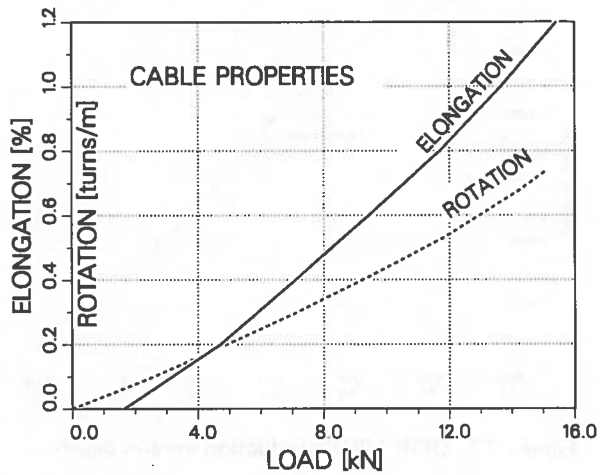

Figure 13. Cable elongation and rotation versus cable tension.

Drill communication

The drill computer measures the following parameters:

1 Cutter load measured as load on the cable
2 Loss of antitorque measured by differential inclinometers
3 Motor current
4 Inclinometer X
5 Inclinometer Y
6 Cable voltage at drill
7 Internal 89V supply
8 Motor voltage
9 Battery current
10 Battery common voltage
11 Motor common voltage
12 Inclinometer voltage reference
13 Leak detector, upper sealing
14 Internal 5V supply
15 Battery temperature 1
16 Battery temperature 2
17 Battery temperature 3
18 Motor power supply temperature
19 Motor temperature
20 Computer temperature
21 Pressure tube temperature
22 Upper power supply temperature
23 Battery voltage, all 5 strings, 55 cells
24 Battery voltage, 4 strings, 44 cells
25 Battery voltage, 3 strings, 33 cells
26 Battery voltage, 2 strings, 22 cells
27 Battery voltage, 1 string, 11 cells
28 Pressure in electronic section
29 Leak detector, motor shaft
30 Leak detector, lower sealing.

In addition screw length (motor rotations), digital status and error codes are transmitted to the surface. Cutter load, loss of antitorque, motor current, screw length and status codes are transmitted every second. The other channels are transmitted on a cyclic basis, providing a complete update every 6 seconds.

The drill is controlled from the surface by setting 7 bits of information: one is the motor ON/OFF switch, two controls the 4 possible motor speeds, one reverse the motor, two control the battery heaters and the last bit control the battery charging. Although the operator can control these bits directly, the normal control is at a higher level, f. ex. the operator can initiate the follwing sequence by a single keystroke:

Fast reverse rotation of the drill. When close to the end of the screw rotate reverse at minimum speed until end of screw. Then motor is switched OFF and screw length is reset.

This sequence is controlled by the drill computer.

Productivity

The time to drill a hole can be calculated knowing run length, winch speed, drilling- and surface time (Johnsen et al., 1980). The Dye-3 deep drilling was performed in 3 shifts, 24 hour a day, 7 days a week except for a weekly 16 hour break. Towards the end of the last season, at a depth of 2000 m, the average run length was 1.9 m including lost runs. Winch speed was limited to 0.6 m/s due to deficiences in the winch. Based on these figures, and a drilling time of 5 min, an effective ground time of 43 min, including the sunday break, hole filtering, regular maintenance etc. can be calculated. Using the above figures, and a cable speed of 0.8 m/s, the time to reach depth x can be calculated as

$$t = 0.034/1.9 * x + 14.5 * 10^{-6}/1.9 * x^2$$

x in meters, t in days.

References

Garfield,D.E., and H.T.Ueda, Resurvey of the Byrd station, Antarctica, drill hole, *J.Glac.*, Vol.17, No.75,29-34,1976.

Hansen,B.L., Deep core drilling in the East Antarctic Ice Sheet: A Prospectus, in Splettstoesser,J.F.,ed. *Ice-core Drilling*. Proceedings of a symposium, University of Nebraska, Lincoln, University of Nebraska Pres,Lincoln, London, p.29-36,1976.

Hodge, B.J.R, R.Bonnaterre and F.Putois,Fast Charging of Sealed Nickel-Cadmium Batteries: Theory and Practice. Proceedings of a Symposium, available from SAFT UK LTD, Castle Works Station Road, Hampton, Middlesex, England,211-231, Brighton 1975.

Johnsen, S.J., W. Dansgaard, N.S.Gundestrup, S.B.Hansen, J.O.Nielsen, and N.Reeh, A fast light-weight core drill,*J.Glac.*, Vol.25, No.91, 169-174,1980.

Klipstein, D.L., The Contributions of Edsel Murphy to the Understanding of the Behavior of Inanimate Objects, *Electronic Equipment Engineering*, Vol. 15,No. 8,91-92, August 1967.

Mellor,M., and P.V.Sellmann, General considerations for drill system design,in Splettstoesser,J.F.,ed. *Ice-core Drilling*. Proceedings of a symposium, University of Nebraska, Lincoln, University of Nebraska Pres,Lincoln, London,p.77-111,1976.

Rand,J.,The Danish Deep Drill, Progress Report: February -March 1979, CRREL, Cold Regions Research and Engineering Laboratory, Hanover NH., Special Report 80-3, 1980a.

Rand,J.,1979 Greenland Ice Sheet Program, Phase 1: Casing operation, CRREL, Cold Regions Research and Engineering Laboratory, Hanover NH., Special Report 80-24, 1980b.

Reeh, N., Antitorque Leaf Springs, this volume.

Shoji,H., and A.Higashi, A Deformation Mechanism Map of Ice,*J.Glac.*, Vol.21, No.85, 419-427, 1978.

Ueda,H.T. and D.E.Garfield,Drilling through the Greenland Ice Sheet,CRREL,Cold Regions Research and Engineering Laboratory,Hanover NH.,Special Report 126,1968.

Ueda,H.T.,and D.E.Garfield, Core drilling through the Antarctic Ice Sheet, CRREL, Cold Regions Research and Engineering Laboratory, Hanover NH.,Technical Report 231,1969.

Zotikov,I.A.,Antifreeze-thermodrilling for core through the central part of the Ross Ice Shelf (J-9 Camp), Antarctica, CRREL, Cold Regions Research and Engineering Laboratory,Hanover NH.,Report 79-24,1979.