Mem. Natl Inst. Polar Res., Spec. Issue, 49, 9-23, 1994

THE NEW IMPROVED VERSION OF THE ISTUK ICE CORE DRILL

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Abstract: The ISTUK deep drill was developed in 1978-1980. The drill is mechanical. The cuttings are sucked from the bits into storage chambers in the drill, and brought to the surface with each core increment (typically 2.4 m in length). Because the actual drilling time is a fraction of the total run time, with most of the time spent going up and down in the drill hole, much emphasis has been placed on reducing the friction in the hole and in reducing the time consumed on the surface. In order to simplify the drilling operation, the steel drill cable uses only one wire with the armour acting as power return. Also, to enhance the reliability of the drilling, most drill control tasks are taken care of by a down borehole processor. The drill was first used during 1979-1981 at Dye-3 in south Greenland, and lately during 1990-1992 at Summit, central Greenland. The Summit drill is physically the same as the Dye-3 drill however, the motor section has been replaced, as have the high-pressure gaskets. The cutters and the core catchers are basically the same, but the angles have been changed slightly. The electronics are new, although the functions performed are unchanged. The winch and the tilting tower are both of new construction and use an electronic variable frequency inverter to drive a standard 3-phase electrical motor. A load transducer is built into the center bolt of the sheave in the drill tower. The readout from this transducer indicates the cable load with high resolution.

1. Introduction

The drill used at the Greenland Ice Core Project (GRIP) drilling at the Summit of the Greenland Ice Sheet (72°34'N, 37°37'W, elevation 3230 m a.m.s.l.) is physically the same drill used for the Dye-3 deep drilling in south Greenland (GUNDESTRUP *et al.*, 1984). Prior to the commencement of drilling, the anti-torque section was lengthened to allow a longer stroke of the hammer. The motor, gear and electronics were updated, however without changing the mode of operation. The bits and core catchers were remanufactured without changing the specifications. The winch, winch controller, surface power supply and operator's console were new, but performed to the same specifications as the previous design. The main changes were implemented as a result of a technological update and the lower temperature of Summit compared to Dye-3. This updated version of the ISTUK drill performed well, producing a stable 170 m/week penetration rate from 200 m all the way to the bottom at 3028.8 m.

2. Cable

At the Dye-3 deep drilling, a 6.45 mm 4-conductor steel armoured cable was used. The wires were tefzel insulated, and this cable worked well. But considering the greater depth of the Summit drilling (3 km *versus* 2 km.), it was decided to change to the next larger size standard cable, Type 4-H28BZ from Boston Insulated Wire. The specification of this cable corresponds to a tefzel insulated version of Rochester Type 4H-281A. The main specifications of the cable are:

Diameter: 7.16 mm
Weight in air: 201 kg/km
Weight in 930 kg/m^3 liquid: 168 kg/km
Breaking strength: 33.4 kN
Resistance of shield: 9.2 Ω/km
Resistance of 4 wires in parallel: 13.5 Ω/km
Maximum voltage: 1000 V
Elongation: 0.5 m/km/kN)

The cable is wound on the winch drum and is controlled by a Lebus groove on the drum and a front steering wheel. After the cable was rewound on the drum with sufficient tension, the spooling worked flawlessly. The cable worked very well, there were hardly any memory effects. The drill was routinely positioned within ±10 cm.

3. Winch

The power requirement of the winch is based on these considerations:

Gravity on 3 km of cable in liquid: 5000 N
Gravity on the drill: 1500 N
Friction on the drill between liquid and drill barrel: 1500 N
Maximum nominal pull in cable: 8000 N
Power at 1 m/s upward speed: 8 kW

Allowing for friction in the winch gear box, 9 kW is the nominal mechanical power required by the winch at the gear input.

At the Dye-3 deep drilling, a 13 kW electro/hydraulic winch system was used. The drive system used an electric motor coupled to a fixed-speed variable-volume hydraulic pump coupled to a toothwheel type hydraulic motor. Taking advantage of the hydraulic leakage in the toothwheel motor, it was possible to position the drill within a few cm.

Because the Dye-3 winch system worked so well, it was tempting to use the same principle at Summit in spite of its low power efficiency. But it turned out that it was very difficult to find a manufacturer who was willing to deliver any hydraulic equipment intended for work at ambient temperatures down to −40°C, even when it was explained that the hydraulic oil was an aircraft type oil with a high viscosity index (little change in viscosity with temperature). Probably numerous problems with gaskets, cold fatigue, et cetera were envisioned.

Therefore, we investigated three types of drive systems:

1) Electrical motor coupled to a continuously variable mechanical gear: This type of drive uses a variable diameter sheave-type gear as in a snowmobile, and previously used in the Dutch DAF cars. The principle is simple, and the efficiency is better than the electro/hydraulic solution, but because the maximum torque increases with reduced cable velocity, the maximum pull in the cable could easily exceed the rating of the cable. Thus, this type could not be used.

2) DC motor controlled electronically: This configuration has a very high efficiency. But

the electronic control of the motor could generate significant Electro Magnetic Interference (EMI). And worse, if an error occurred in the electronic control, the maximum torque delivered could be more than 10 times the nominal torque. Thus, the pull on the cable could exceed the rating of the cable.

3) Variable frequency drive with a 3-phase motor: The electronic control of the motor would be a source of radio interference, but the system is basically safe: even in the case of an electronic control malfunction, the maximum pull on the cable can never exceed 3 times the nominal pull. Therefore, it was decided to use this type of winch drive system. The advantage of this system is that the winch is remarkably simple: the winch drum is coupled to the exit shaft of the drive gear, and the winch motor is bolted to the inlet shaft of the same gear. While the mechanical solution is simple, all problems with winch speed, torque, direction of rotation et cetera have to be taken care of by the electronics. A variable frequency drive can relatively easily reduce the speed to 10% of the nominal, and still provide enough braking torque. We tried several different types of inverters before we found one that could rotate the motor down to the slip of 5%. Furthermore, by reversing the field (giving upward torque while slowly lowering the drill), we obtained a speed of zero, although the winch required careful attention by the operator in this speed range. The inverter is of the "Variable Vector Type", feeding the motor with full voltage pulses of varying frequency and width.

During drilling, 1 to 2 m of cable has to be paid out while the drill penetrates downward. This was done in steps of a few centimetres, by momentarily releasing the winch brake. The final specification of the winch system is:

Electronic unit: Scandialogic, type SL-15000-3, 15 kW nominal motor rating.
Electronic braking, firmware modified to allow zero motor speed.
Maximum torque limited electronically.
Minimum and maximum frequency adjustable.
Temperature: rated 0° to 45°C. Works at –15°C. Cabinet heated.

Motor: Standard 3-phase 3*380 V, 11 kW nominal shaft power, 12.6 kW electrical power.

Winch: Drum is Lebus-grooved, with a storage capacity of 4 km of 7.1 mm cable.
Gear box is designed for a 15 kW motor.
Empty weight of winch is 2 t.

Cable pull: Nominally 15 kN on inner layer, 10 kN on outer layer.
Maximum torque is 200%, *i.e.* the maximum pull in the cable, even at the inner layer on the drum is less than the cable breaking strength of 33 kN.
Motor can run at 40% over torque for 40 s.

The winch has worked now for three seasons without requiring other maintenance than routine lubrication. The cable could be positioned within a few centimetres, and the winch was powerful enough to break the core without having to use the hammer in the anti-torque section. During the last few runs of the drilling, the ice core required significant force before the core broke off. In fact, the force was so high that an electrical short occurred in the cable. After disconnecting the faulty conductor, the drilling proceeded. At the end of the next run, the core break was so hard that one of the three remaining electrical wires in the cable broke. It was then time to declare the drilling terminated. In this last core break, based on cable elongation (the cable load transducer was overrange), the cable tension must have been the maximum possible, *i.e.* 80% of the cable strength.

4. Casing

During the Dye-3 drilling, a steel casing was used (RAND, 1980). The casing was sealed at the bottom by refrozen water in the lower 0.5 m of the casing. This system created several difficulties: (1) rust from the casing penetrated the seals in the drill, requiring frequent disassembly and cleaning, (2) the refrozen water inside the casing was chopped off by the drill, and blocked the drill, (3) the casing was not tight, there were leaks both at the casing bottom and at several connections and (4) the individual casing tubes were not centred, causing the drill bits to break while the drill passed down in the casing.

After recommendation from our Australian colleague (Vin MORGAN, personal communication) a special fiberglass casing was used.

Each individual sections of this casing is sealed with a double O-ring, and the sections are held together by a steel wire (Fig. 1). The system worked well, and the casing was mounted in a single day.

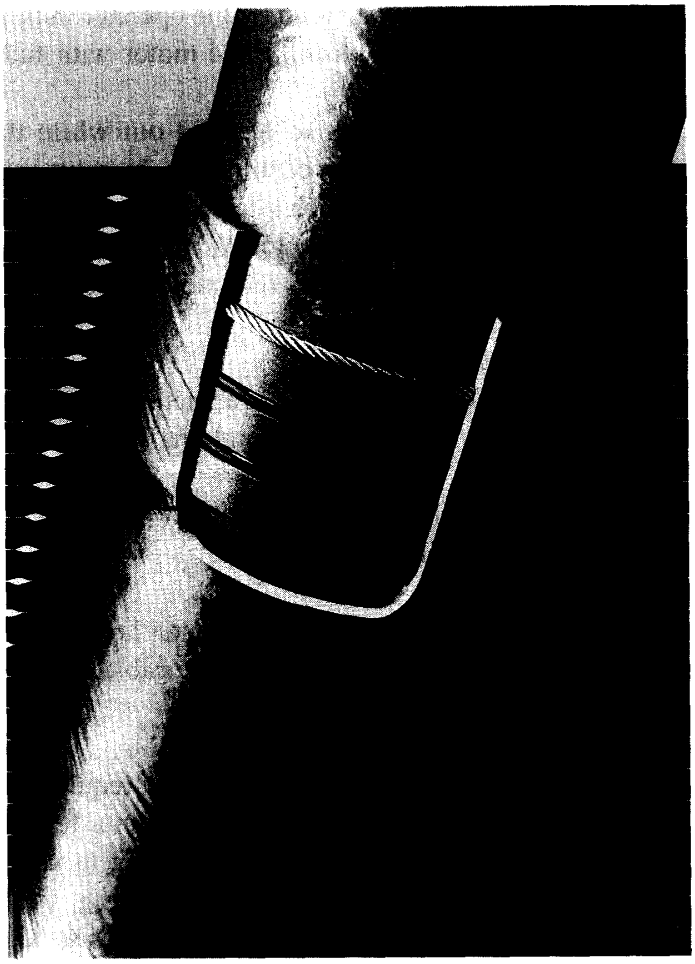

Fig. 1. The casing interconnection.

The casing, which has an inside diameter of 200 mm requires a 255 mm hole. Because no wide diameter drill was available, the hole is created by gradually reaming of a 104 mm shallow hole (Fig. 2). The casing rests on the 16.5 mm wide shelf between the 255 mm casing hole, and the 222 mm hole that the last casing section penetrates. The casing is sealed at this shelf because the high pressure from the weight of the casing (10 kg/m) will deform the ice where the casing rests, and create a seal. This worked very well, and one year after installation the casing was tight. The bottom of the casing is 96 m below the surface. The bottom of the casing is inclined 1°. This inclination is caused by the inclination of the 104 mm shallow pilot hole. Though the hole started vertically at the surface, and great care was exercised during the shallow drilling, it was not possible to obtain an inclination less than 1°. Because the first shallow hole drilled was inclined 1°,

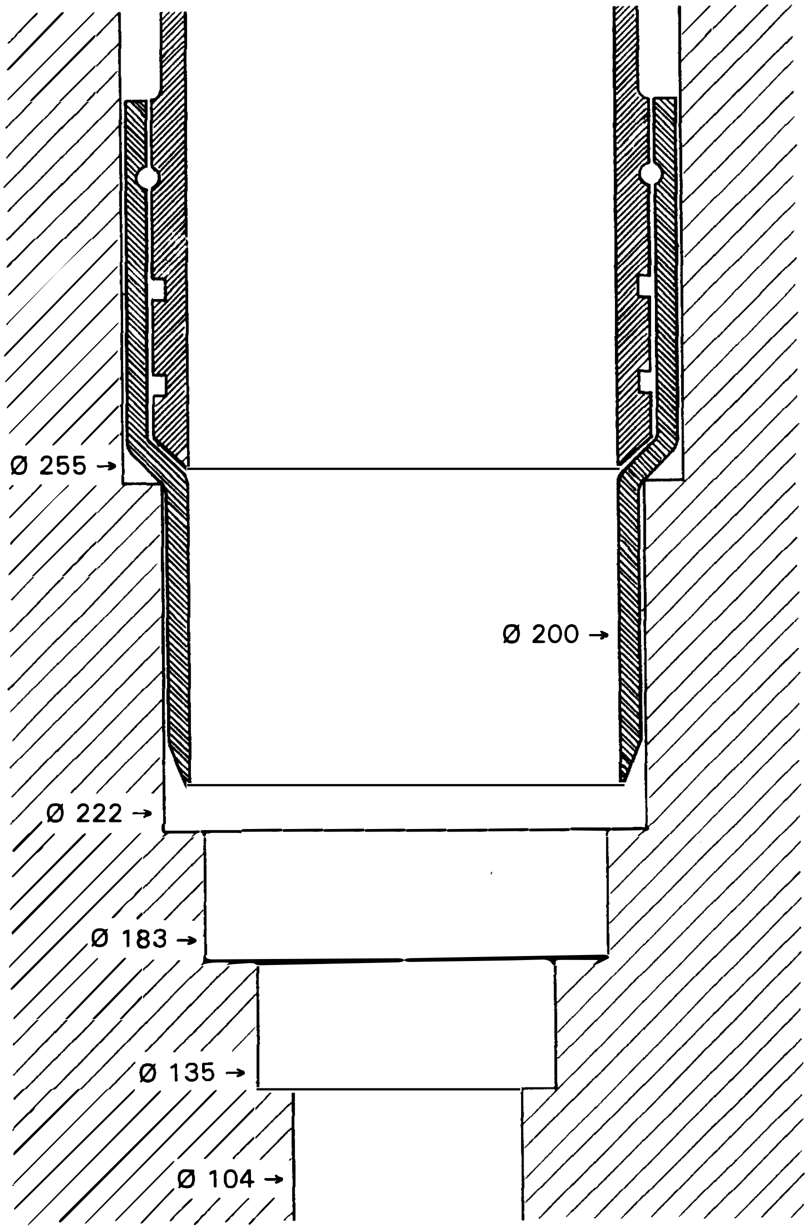

Fig. 2. Bottom of the casing, showing how the casing rests and seals to the ice. Also shown is the stepwise enlargement of the original 104 mm shallow hole to the casing diameter of 255 mm.

another attempt was made, however, without better results. Logging of both holes revealed that the holes started to deviate from the vertical at a depth of 30 m.

5. Tower

During the Dye-3 deep drilling, the tower was made from an aluminum tube supported by guy wires. Because the guy wires hampered the access to the drill, the tower used at Summit is a stainless steel grid construction with a 35 cm frame size (Fig. 3). This construction gave the 11 m long tower sufficient rigidity. The drill rests on supports along the side of the tower when the tower is horizontal. This allows unobscured access to the drill in its full length. However supports could engage the drill when it passed along the tower. This risk was minimized by giving the tower a slight "overtilt" in the upright position. With the tower tilted 0.9°, the distance between the supports and the drill is 10 cm at the floor of the drill trench, and 20 cm at the bottom of the tower in the inclined drill

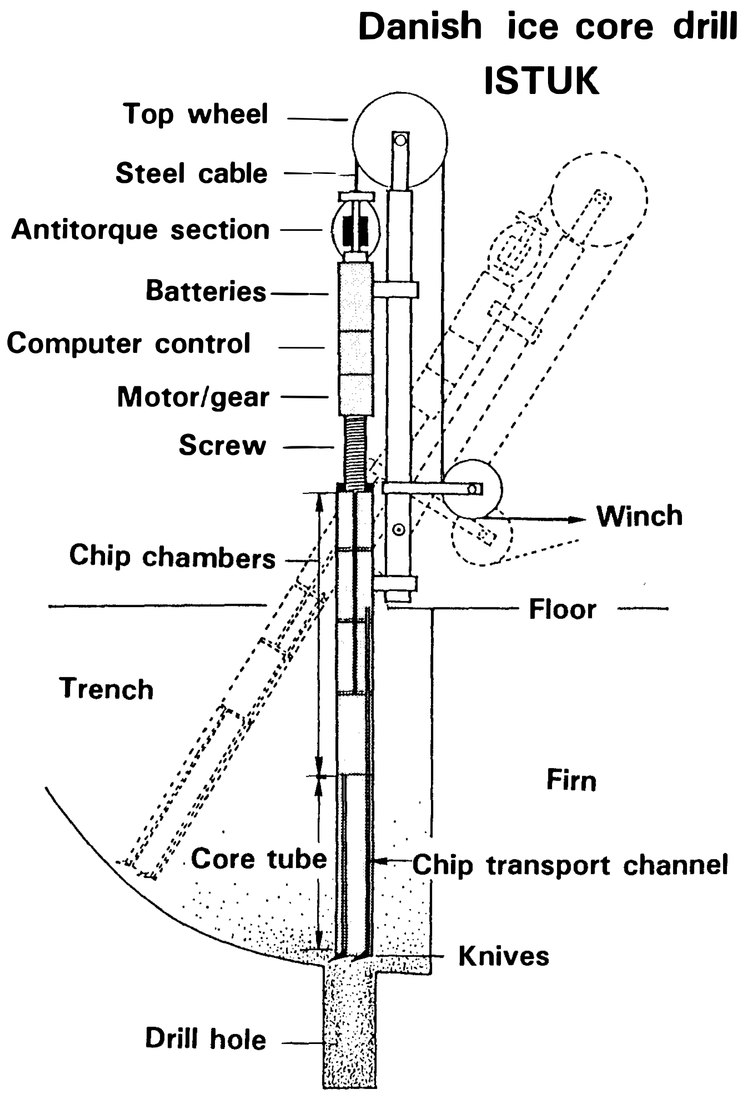

Fig. 3. The drill shown in vertical and slanted configuration.

pit. This means that except for the upper support, close to the top wheel, there is no risk of the drill hanging up on the supports. Because of the inclined tower, there is a horizontal force in the tower caused by the load in the cable. This horizontal force does not exceed 550 N, and therefore is of no importance.

The tower is tilted using a variable frequency AC motor. As for the winch, the use of an electronically controlled AC motor gives a well-defined maximum torque, and an easily varied speed. The tower tilting worked well, and performed a 90° tilting in 30 s.

A strain gauge sensor is built into the center bolt of the top wheel on the tower. This sensor shows the load on the drill cable, and is both frictionless and of high resolution. This sensor is the primary indicator for the operator, both for determining when the drill is touching bottom, and when there is a requirement for more cable during drilling.

6. Electronic Section

The electronic section of the drill used at Dye-3 worked well, so, although completely redesigned, the electronic package used at Summit performed to the same specifications as the previous package (GUNDESTRUP *et al.*, 1984). The modified package was shorter, allowing a longer DC motor, and tested to below –32°C. The motor is a rare earth type, Type TM 2045-3073-C, 60 V, 7.9 A, 2400 RPM from Industrial Drives. The motor is directly coupled to a Harmonic Drive, 1:80, reduction gear size 25. The motor- gear section was rebuilt using new types of gaskets and ball bearings. It still keeps the motor in the low-pressure electronics section, and transmits the torque to the barrel through a slowly rotating shaft packed to sustain the pressure as well as the low temperature. This worked well, and the same two electronics and drive sections, were used for the entire drilling.

7. Battery

A critical part of the drill is the battery that supplies the greater part of the power to the drill motor. In the Dye-3 version of the drill, a standard NiCd battery package consisting of 55 pcs 2Ah Saft VR cells in series, heated to 20°C, was used. Due to the unknown power requirement at Summit, several other types and brands of batteries were tested in a special computerized test setup. The batteries were cycled ten times, with 6 amps discharge current and 2 amps charge current. Most batteries that failed this test did not develop a sufficient voltage increase when fully charged. A Gates type battery had a high capacity and a linear voltage increase with charge, but because one battery failed (exploded) during the test, it was decided to continue with the Saft VR NiCd battery type. Then, the VR types were selected for capacity and voltage, and the best two-third of the batteries were selected.

The batteries worked well. The same two power packs were used for the 1990 and 1991 seasons, drilling down to 2.3 km. At the end of the 1991 season, a marked reduction of capacity was experienced. Two new sections then powered the drill in 1992 until bedrock was reached at 3028.8 m. No failures were experienced.

8. Cold Fatigue

At Dye-3, with ice temperatures of –20°C, we had no problems with cold fatigue. The Summit drilling took place in ice 12° colder, so we expected some problems. The most critical part is the drill antitorque section. If this breaks, the drill and the hole might be lost. Thus, an antitorque section (15 cm longer than that used at Dye-3) was manufactured from stainless steel, which is believed to be resistant to cold fatigue. In fact, the only problems we had were two motor exit shafts that sheared during slow rewinding of the drill barrel to a mechanical stop. The shaft was made from "Regin 3" compound, maximally hardened to 59 HRC. It was replaced with a shaft of the same material hardened to 55 HRC, and this shaft survived the program. However the conclusion that the less hardened shaft is good enough is not well founded because the hole temperature had increased some degrees at the depth where the shaft was replaced. Cold fatigue is definitely a problem at –32°C.

9. Operation

The operation was almost unchanged from the procedures used at Dye-3 (Fig. 4). The main parameter which ensures stable drilling is the correct cutting angle. Also, the sides of the cutters were ground to keep the contact area between the cutter and the ice to a minimum. In practice, the side of the cutter in contact with the hole wall should be less then 0.4 mm. The inner side of the cutter should be ground to achieve clearance right behind the cutting edge. We found that when the area in contact with the ice was 1 mm wide at each cutter, the drilling was unstable. The chip chambers were vented on the way down until a depth of 600 m. Deeper than that, the pressure is so high that no venting is needed. Also, the drilling was so stable that routine checks on the suction system were only performed once a week.

It is essential to keep the number of cuttings in the hole liquid to a minimum, both to ensure fast winch speed and stable drilling. At the Dye-3 drilling, the core barrel was used to filter the liquid, storing cuttings above the ice core. This both reduces the core length considerably, and reduces the lowering speed of the drill in the hole. Therefore, this filtering method was not used at Summit. Instead a filter was mounted on the drill cable, above the drill when required. Because the lowering speed of the drill in the hole is one of the main factors that limits the productivity, a gauge in the drill measured the weight of the drill on the cable. By observing this gauge, the operator could control the winch speed so that the drill was nearly free falling in the hole. By keeping the hole liquid clean, it was possible to obtain a lowering speed of 1 m/s, and a hoisting speed from 90 cm/s at 3 km depth to 1.25 m/s close to surface. The hoisting speed at deeper depths was frequently limited by the available power.

The cutting angle is very critical for both the power needed for cutting, and for maintaining a stable drilling. If the cutting angle is too steep, the drilling power increases rapidly, and finer (and more difficult to transport) ice cuttings are produced. If the angle is too small, the chips get too coarse, and they may block the entrance to the suction channels. The best cutting angle was 45° in the beginning, reduced to 42° at intermediate depths and again at 45° close to the bottom. The changes are most likely caused by

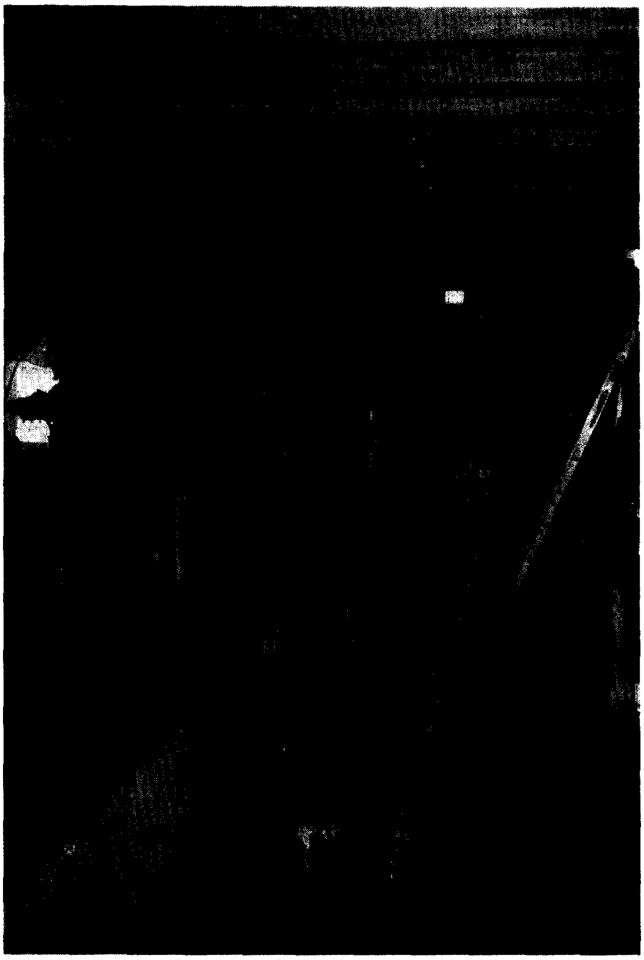

Fig. 4. The drill, winch and inverter in the background at left.

changes in crystal size, orientation and temperature.

The energy used for cutting increased somewhat with depth. Also, the power increased sharply with increasing core length. With a typical motor current of 7.5 A, 1 A no load current, 75% efficiency of the gear section and a 7 minute drilling time for a 2.4 m long ice core, the specific energy (the energy required to cut 1 m^3 of cuttings) is 10 MJ/m^3. At Dye-3, the specific energy was 16 MJ/m^3. The improvement can be explained by the better cutters used during the Summit drilling. At Dye-3, we had to use damaged cutters because the corners were hit when the drill was lowered in the steel casing.

10. Hole Liquid Density

The drill requires a hole liquid with a density higher than the density of ice. Apparently, if the hole liquid density gets too low, ice chips fall to the bottom of the hole, and when the drilling starts, the chip mixture is too concentrated for the suction system to work properly. Therefore, we attempted to keep the hole liquid density as close to 920 kg/m^3 as possible, and in practice a value of 935 kg/m^3 was required to ensure stable drilling. This density is a bit high in view of the lifetime of the hole. Also, for the first runs of each season, we had to use a high-density liquid (say 1050 kg/m³) in the drill. It seemed that some high-density slush had collected at the bottom of the hole during the winter.

Considering that the softest part of the ice is at the bottom, the hole will deform in a way to establish pressure equilibrium between the hole pressure and the ice at that depth (HANSEN and GUNDESTRUP, 1988). With a hole liquid density of 935 kg/m³, the hole will deform over time to obtain the correct pressure at the bottom of the hole. This will result in a stand of the liquid of 2950 m, 80 m below the snow surface. The result will be an *under pressure*, which in the upper part of the hole can be as high as 5 bars, and the hole will thus close at the top with time. In the Dye-3 deep hole, the stand of the liquid is 110 m below the surface, corresponding to an *under pressure* of 7.8 bars at this depth. With an ice temperature at Dye-3 of −20°C, the deformation required reaming the top of the hole in 1987, 6 years after termination of the drilling, prior to logging the hole. It is difficult to estimate, for how long a time the GRIP hole will be accessible because the snow is more homogeneous at Summit, and the deformation rate is highly dependent on temperature and pressure, as well as time.

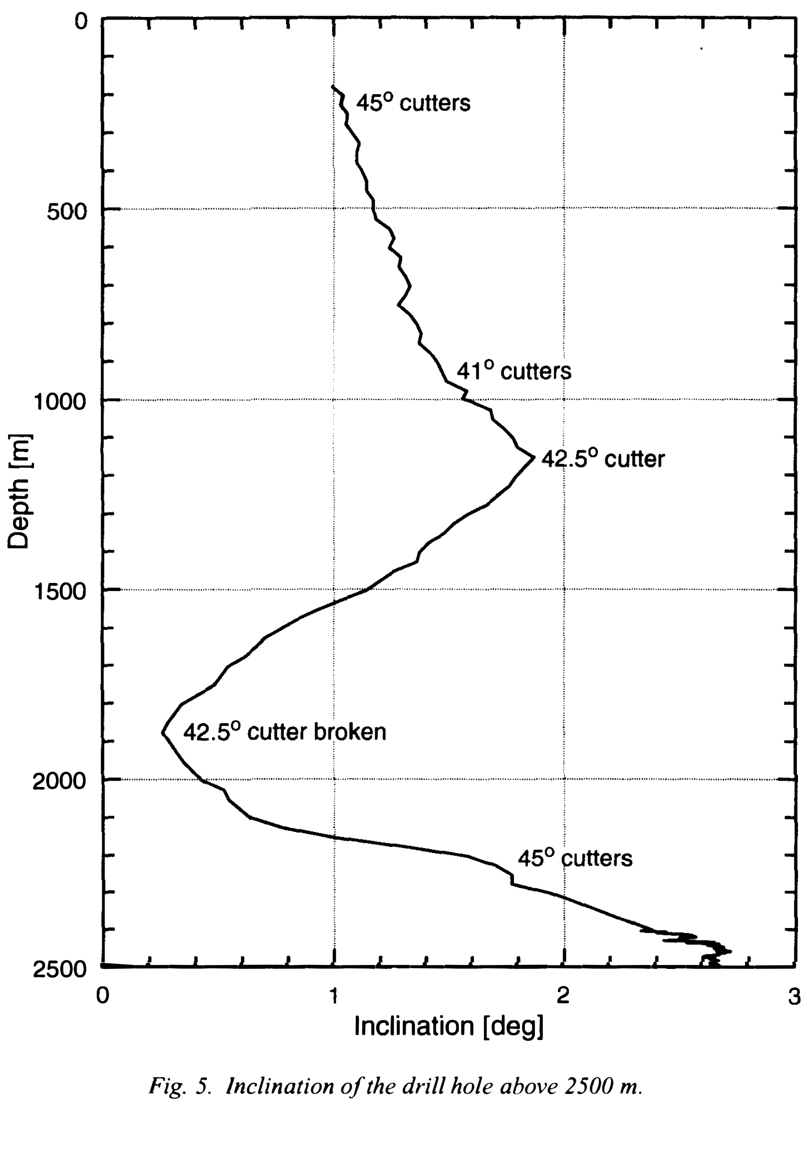

Fig. 5. Inclination of the drill hole above 2500 m.

11. Hole Inclination

A special problem is to keep the hole vertical. The drill is 11 m long and 130 mm in diameter. The lower part of the drill is relatively flexible, and there is little natural rigidity. Thus it can be expected that the drill will tend to deviate more and more from the vertical with depth. In order to compensate for this natural instability, the cutter load is *negative.* After the drilling is started, the operator pulls back in the cable, creating up to 500 N negative cutter load. This negative cutter load is maintained throughout the entire drilling cycle, and is monitored by the cable load transducer on the top of the drill tower. The gauge on top of the drill measures the load between the cable and the drill. But, due to friction in the bearings, this transducer did not give the same resolution as did the top wheel, which routinely responded on 10 N changes in cable load.

This procedure worked well. From the 1° inclination at the bottom of the casing, the inclination increased slowly until 1100 m. At this depth, a better cutter geometry was found, and this reduced the inclination until a minimum of 0.3° at 1900 m (Fig. 5). Then at that time the supply of this type of cutter was exhausted. The bits had to be changed, and

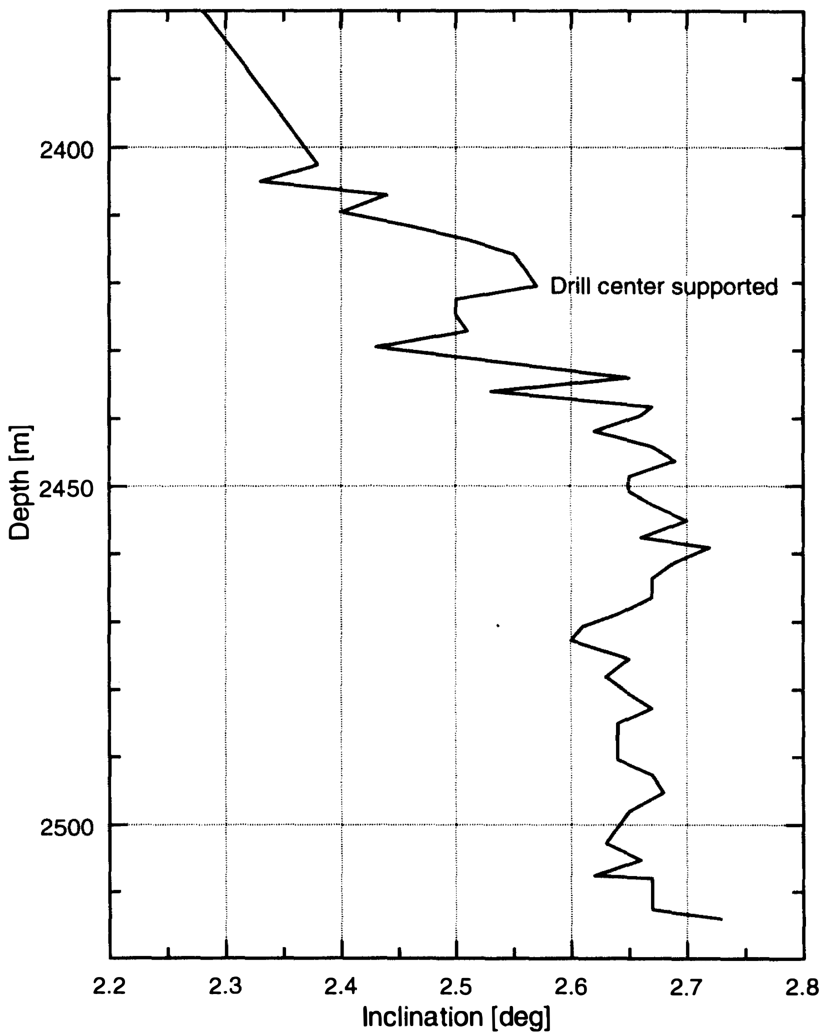

Fig. 6. Drill hole inclination from 2380 to 2520 m.

one of the channels was resoldered at one spot with a harder, higher temperature solder. Whether due to the changed bits or the slight asymmetry caused by the last repair, the inclination increased rapidly. At a depth of 2400 m, the inclination was almost 2.4°, and the situation was considered unstable. A modification to the drilling software program for the surface console was made that reduced the noise in the inclination reading to 0.1°, and the inclination was monitored run by run. Twenty metres deeper, the inclination reached 2.55°, and it was decided that the drilling could only continue for a few hundred metres without again changing procedures. The *negative* cutter load was kept at a maximum so the only alternative was to make the drill appear more rigid. This was accomplished by lengthening the spacers at the top of the drill barrel on the nut holder on the screw. Previously these spacers centred the drill within 0.5 mm in the hole. The spacers were now adjusted to ensure that the drill at this point was centred in the hole within 0.1 mm, thereby effectively using the hole wall to support the drill. As shown in Fig. 6, this worked immediately. First, it seemed that the inclination decreased, but this was only a transient situation until the drill found its new state. Thereafter, the inclination only increased

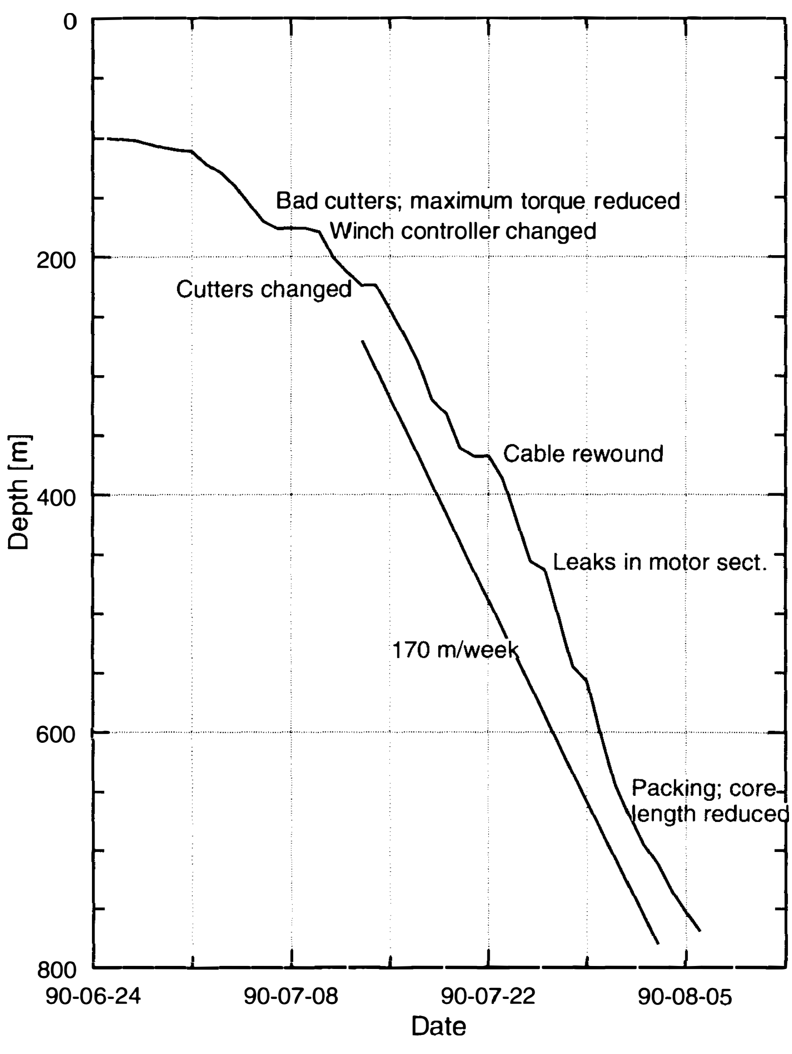

Fig. 7a. Drill hole depth versus date in 1990. There were numerous problems, but they were overcome without major penalties in penetration rate.

gradually, reaching 3° at 3000 m. One drawback of using these spacers is that the drill is not able to reduce the hole inclination, as we observed from 1100 m to 1900 m. Nonetheless the drill had lost this self stabilising capability.

12. Performance

The drilling started June 25, 1990, and the 1990 drilling season ended August 6 at a depth of 769.5 m. In 1991, the first core was recovered on June 4, and the drilling terminated at a depth of 2321 m on August 7. In the last season, the first core was recovered on May 27, and the drilling stopped at a depth of 3028.8 m July 12, 1992, after penetrating 6.3 m of silty ice. The operation went well. The friction in the high-pressure gaskets around the motor exit shaft was negligible, and the only problem with the high-pressure seals was that at depths around 500 m, the seals could from time to time suddenly release approximately 1 m*l* of hole liquid into the pressure section, probably due to the low temperature of the compression O-ring. This liquid was trapped in the volume designed for this purpose, and the leaks were monitored by pressure transducers. At no time we

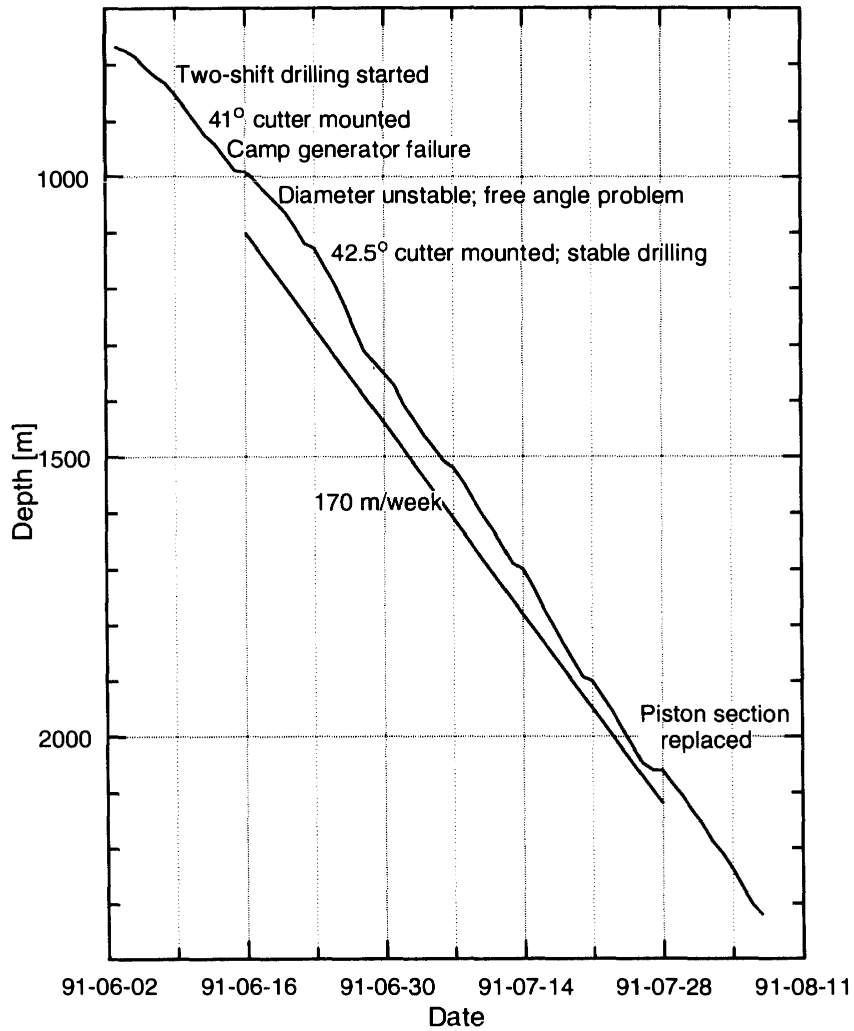

Fig. 7b. Drill hole depth versus date in 1991. The drilling performed well without major problems.

experience a non-controlled leak. At deeper depths there were no leaks. To ensure the best possible seating of the gaskets, the motor was run slowly during the first lowering of the motor section down the hole after the gaskets had been replaced. Also, the sealing system around the motor shaft was changed from two teflon rings with elastomeric compression to one high-pressure teflon ring and a secondary Variseal thin-walled teflon V-type gasket. With this dual sealing system, no leakage was observed.

The suction channels required frequent maintenance. During drilling, the under pressure in the channels could go as low as 6 bars, and when the channels were cleaned at the surface, the overpressure could be 6 bars. These pressure changes caused the 1 mm stainless steel wall of the channels to move, causing fatigue breaks in the soft solder fixing the channels to the drill barrel. Typically, repairs were made once a week, mostly on a routine basis.

Figure 7 shows the penetration rate for the 3 drilling seasons. After an initial period of one to two weeks, the penetration rate was close to 170 m/week from the 200 m depth in July 1990, until silty ice was encountered at a depth of 3022 m in July, 1992.

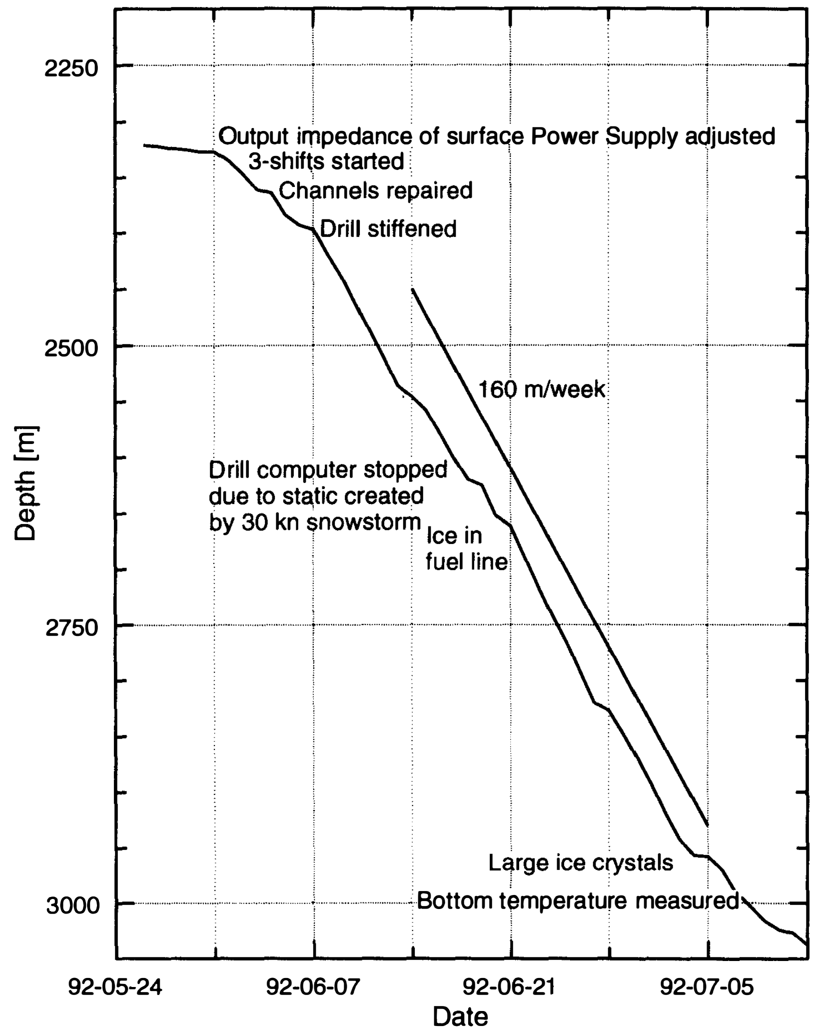

Fig. 7c. Drill hole depth versus date in 1992. The drill performed well after the initial adjustments, and the only critical adjustment was the change to the drill made at a depth of 2420 m.

Improvements in procedures and experiences compensated for the longer time used to lower and raise the drill.

13. Conclusion

The drill worked well throughout the three drilling seasons. The position of the motor-gear section in the pressure chamber worked satisfactorily, and the rotating shaft was sealed using conventional hydraulic gaskets. The battery package had a lifetime of more than one season. At no time, were there any problems with the 55 batteries powering the drill. The core breaks were relatively easy, seldom requiring more than 4000 N to break the core. At no time was the hammer in the anti-torque section used to break the core. This is contradictory to our experiences from Dye-3. The change could be caused by the drilling being at the Summit, and that the hole is nearly vertical, causing the C-axis of the ice crystals to be oriented in the direction of the drill. The core quality was excellent outside of the brittle zone (600–1300 m), and manageable in the brittle zone. This means that the discrepancy between core drilled and core logged, is expected to be better than 2 m. Also, no part of the core is missing. The drill hole was kept nearly vertical, although the mechanism involved in the changes of the hole inclination changes is not quite understood.

Acknowledgment

This work is a contribution to the Greenland Ice Core Project (GRIP), a European Science Foundation Programme with eight nations collaborating to drill through the central Greenland ice sheet.

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(Received May 25, 1993; Revised manuscript received January 24, 1994)