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INSTRUMENTS AND METHODS

A FAST LIGHT-WEIGHT CORE DRILL

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Abstract. A core drill capable of drilling to more than 100 m depth in cold ice is described. It is designed with a view to fast operation and easy transport, core handling, and maintenance.

Résumé. *Une sonde à carottage légère et rapide*. On décrit une sonde à carottage pouvant aller à plus de 100 m de profondeur dans la glace froide. Elle est conçue en vue d'accélérer le prélèvement et de faciliter le transport, la manipulation de l'échantillon et sa conservation.

Zusammenfassung. *Ein schneller und leichter Kernbohrer*. Es wird ein Kernbohrer für Bohrungen bis zu mehr als 100 m Tiefe in kaltem Eis beschrieben. Seine Konstruktion war auf schnellen Vertrieb und Einfachheit im Transport, in der Kernbergung und im Betrieb ausgerichtet.

In ice-coring terminology "shallow depths" usually means less than 100 m. Disregarding the coldest parts of East Antarctica, the firnification process essentially terminates at shallow depths. It is therefore an obvious, yet severe demand that a drill be able to recover unbroken core pieces of any density from approximately 400 to 900 kg m^{-3}. Furthermore, the drill should be easy to transport, i.e. lightweight and of small dimensions, and fast to operate.

The famous SIPRE auger, the Icelandic drill (Árnason and others, 1974), the Swiss drill (Rufli and others, [c1976]), and the U.S.A. CRREL shallow drill (Rand, [c1976]) are mechanical drills, and the device presented here includes ideas from all of them, e.g. the cutters, the chip transport and collecting systems, and the anti-torque system. Nevertheless, some of the modifications may be of interest to possible future shallow drillers.

The Danish drill has been developed under the Greenland Ice Sheet Program (GISP), which is a joint Danish–Swiss–United States effort. The drill has a total weight of 300 kg, including winch, cable, "tower", electronic control system, generator, fuel, and packing materials. The heaviest item is the winch, weighing 140 kg, including motor, gear, 200 m of cable, and a wooden container. The largest dimension is 3.5 m. Hence, the entire equipment can be transported in a Twin Otter aeroplane, or it can be assembled on a 3.5 m Nansen sledge and pulled to the drill site by a skidoo. In the latter case three people need a total of sixteen working hours at the drill site for drilling and packing 100 m of core.

The drill is usually operated within a tent raised over a trench 0.3 m wide and 1.3 m deep. The tent protects against bad weather and direct sunshine that otherwise causes melt water on the drill and, upon refreezing, operational troubles in the hole. The drill and "tower" can be turned into a horizontal position (Fig. 1) one metre (i.e. comfortable working level) above the surface to facilitate the removal of chips and cores (78 mm diameter, 1 m length). In upright position the device reaches from 2.3 m above to 1.2 m below the surface.

The winch is made of hard aluminium, except for the steel cylinder and shaft. It has a built-in 1 kW motor fixed to the cylinder ("Mavilor", model 1000, disc-type, d.c., diameter 202 mm, length 126 mm, weight 12 kg, 3 000 r.p.m. rated speed). The shaft is modified so as to fit the reduction gear directly (Harmonic Drive, model HDUC 50-80-2A; reduction factor 80 in one step; diameter 170 mm; length 110 mm; weight 4.5 kg; rated torque 520 N m). The motor-gear assembly is bolted on the inside of the cylinder, and the gear exit shaft is fixed to one of the outer aluminium plates that carry the winch. The remarkable gear data are due to an unconventional design that is highly recommended for winch as well as for

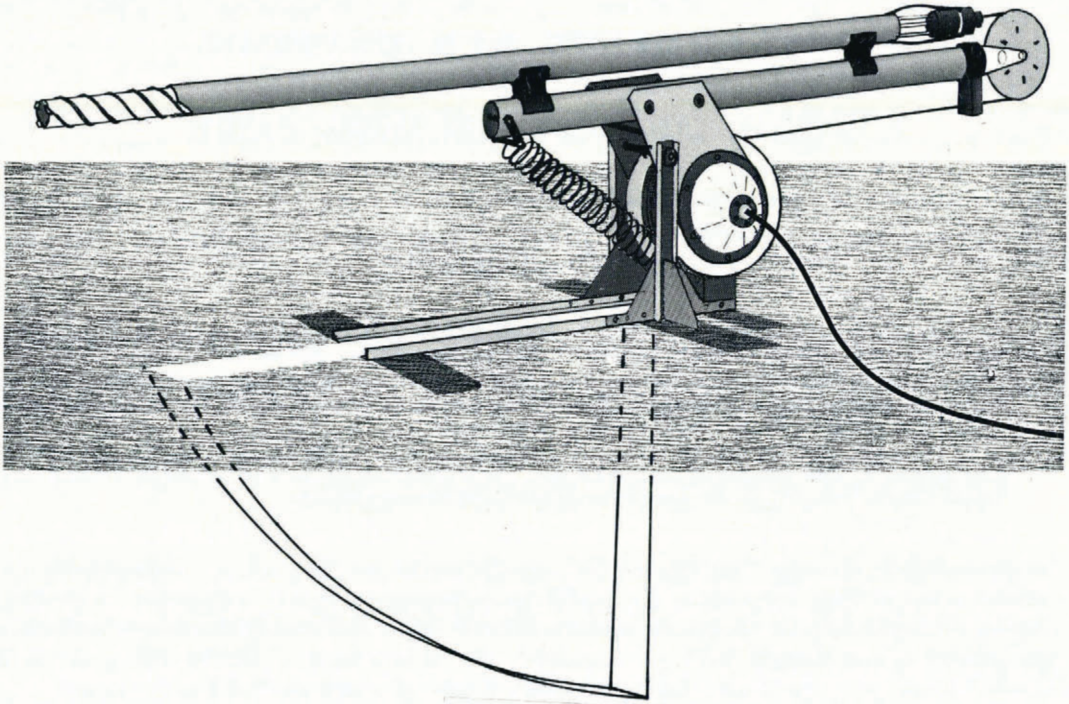

Fig. 1. The drill turned into a horizontal position for removal of core and chips. In its vertical position, it reaches from 2.3 m above the snow surface to 1.2 m below. 100 m depth can be reached in 10 h.

drill constructions, because of its low weight and volume. The cone at the end of the winch (Fig. 1) contains slip rings for the winch motor and the drill cable. The rotation of the winch can be adjusted continuously within the range +1 to −1 r.p.s., giving a maximum hoisting or lowering speed of more than 1 m s^{-1}.

The cable is a 5.6 mm steel armoured U.S. Steel product (type 4H22RB; breaking strength 20 000 N; minimum bending radius 150 mm; net weight 12.3 kg per 100 m; d.c. armour resistance 1.5 Ω per 100 m) with four insulated conductors (d.c. resistance 8 Ω per 100 m). Three of the conductors are used in parallel for power transfer to the drill motor, the fourth one for transfer of electrical control signals. The armour serves as a common return.

The aluminium wheel on top of the "tower" (to the right in Fig. 1) is provided with ten small magnets. When turning, they activate three reed switches giving electrical signals indicative of the cable speed and direction. One complete turn of the wheel corresponds to exactly 1 m cable length.

At the drill, the cable is fixed by a "Dynagrip" termination to a hammer block (see below) through a system of ball bearings, which prevents cable twisting in case of antitorque failure. In such situations three steel supporters on the rotating antitorque system pass a microswitch on the cable, thus producing alarm signals through the fourth cable conductor for detection on the surface.

The antitorque system has three leaf springs 120° apart, 500 mm long, 20 mm wide, and 2 mm thick. They are pre-bent to a fourth-order parabolic shape, which ensures a uniform load distribution along the length of the spring that is in contact with the hole wall. By changing the distance between two hinges supporting each spring, the rise of the springs can be adjusted from high values in the upper firn to low values in solid ice. In the latter case each spring exerts a 300 N force on the hole wall, sufficient to prevent rotation of the drill and low enough to ensure the necessary load on the cutters. The flexibility of the springs is important, when the drill passes refrozen melt layers in the firn.

A steel hammer block is mounted between the springs. It weighs 7 kg and glides along the three supporting rods over a distance of 100 mm. Breaking of a drilled core is done by ramming the block against the upper stopper. The same procedure serves to disengage the drill in case of sticking, and it is much more efficient than a smooth pull by the winch.

The motor-gear section in the drill is 290 mm long (ball-bearing support for the exit shaft included) and has a 97 mm diameter. It is built principally the same way as the winch motor-gear section. Two "Mavilor" d.c. motors (model 80) are coupled in series and work on a "Harmonic Drive" (HDUC 20-80-2A) reduction gear converting the rated 6 000 r.p.m. into 1.25 r.p.s. The power consumption is 230 W no-load, and 450 W when cutting ice at a penetration speed of 7 mm per revolution. The bottom of the motor-gear section is bolted to the outer core barrel, and the moment is transferred to the inner core barrel through a simple shaft, strong enough to withstand the maximum 20 000 N pull from the cable.

The core barrels are both made of stainless steel, aligned by point heating to within ±0.5 mm over the entire tube lengths. The outer barrel is 2.65 m long and reaches from the bottom of the antitorque section and all the way to the cutters. It has an outer diameter of 101.6 mm and a 2 mm wall thickness. On the inside, the outer core barrel has 20 closely spaced grooves (0.4 mm deep) parallel to the axis enhancing the upward transport of the chips. The inner barrel is 2.35 m long; its inner diameter is 81 mm and the wall thickness is 2 mm. On the outside, it is provided with three lead auger flights with a pitch of 180 mm. Each of the spirals leads from a cutter at the lower end to a hole at the top, allowing the chips to deposit in the upper part of the core barrel.

The cutters are mounted on a stainless steel block at the end of the spirals. Using three instead of the conventional two cutter knives gives smoother cutting without vibration of the drill, which is considered to be one reason for the good core quality obtained; another reason is probably that the central part of the cutter edges were rounded to a radius of 2 mm, strengthening the footing of the core; and a third reason is that the clearance angle chosen (15°) gives a rate of production of coarsely grained chips appropriate for immediate removal by the spirals. With smaller clearance angle the chips becomes too fine, with greater clearance angle too numerous, to be removed immediately without packing and subsequent breaking of the core.

The width of the cutters is 13 mm leaving a 1 mm clearance between the hole wall and the outer core barrel, and a 0.1 mm clearance between the core and the inner surface of the drill head.

The electronics consist of (1) power supplies for the winch and the drill, and (2) control systems. The power supplies are single-phase silicon controlled rectifier types, delivering 0–160 V, 18 A for the winch, and 8 A for the drill. The drill supply is able partly to compensate for losses in the cable. The control system converts the turning signals from the top wheel into a direct-read-out depth indication. Furthermore, a buzzer is switched on if alarm signals are received from the drill indicating insufficient antitorque. All units are powered by a 3 kW, single phase, two-stroke "Bosch" generator.

The performance of a preliminary version of the drill was tested in May 1976. In 1977 a drill team consisting of Sigfus Johnsen (leader), David Fisher, Jan Nielsen, and Carsten Rygner used the final version on several locations on the Greenland ice sheet, both in the percolation zone (Dye 2 and Camp Century) and in the dry zone (North Central, lat. 74° 37′ N., long. 39° 36′ W.). A total of 800 m of core was recovered to a maximum depth of 110 m. At the end of the season, when the optimum shape of the cutters had been worked out, drilling a 100 m core took only 10 h. The average length of the core increments recovered per run was 1.2 m in firn and 1.0 m in ice. The quality of the core was excellent, i.e. no "wafering" and only very few unintended breaks. The only difficulty occurred at 110 m depth, when falling ice crystals from the upper part of the hole collected on top of the hammer block, which made it stick to the flat impact surface above. The drill was stuck for several hours, and had to be disengaged using glycol. The risk of future accidents of this kind was minimized by providing the support rods with rings for impact with the block.

Future modifications which we recommend, although the drill worked well as described, are as follows:

1. The spirals should be brushes (Rand, [$^{\text{c}}$1976]) or nylon (Rufli and others, [$^{\text{c}}$1976]) screwed onto the inner core barrel, in order to avoid the risk of loosening the glueing due to frequent temperature changes.
2. Small support blocks of the same width as the cutters should be mounted between the cutters for better definition of the cutting depth.
3. The cutting head should be provided with core catchers allowing larger clearance between the core and the drill head.

In view of the fast operation of the drill, we would not hesitate to use it to greater depths in cold ice with the additional modification:

4. Fast and complete compensation of energy losses in the (longer) cable by regulation of the output voltage to ensure a constant voltage on the drill motors.

Blueprints of drawings will be available in late 1980.

How deep? Since essentially no clearance is left between the cutters and the hole wall, any degree of hole closure causes radial forces on the cutters and, consequently, a resistance to vertical movements of the drill. This resistance is highest some distance above the drill, depending on the speed of penetration, and it can be overcome as long as the pull in the cable during hoisting, and the gravitational force during lowering of the drill, are able to make the cutters scrape away the "excess" of material along the hole wall. It is difficult to define the

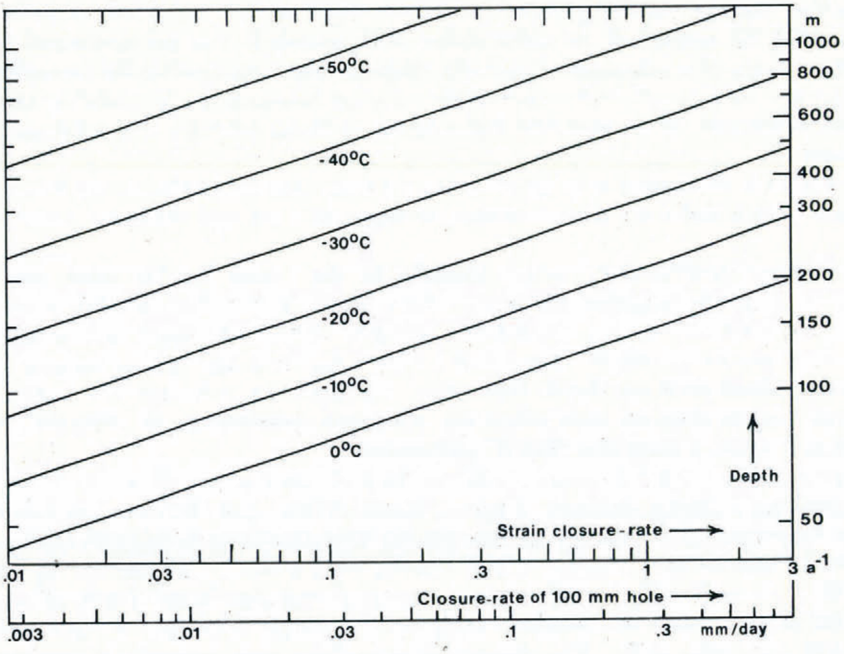

Fig. 2. Strain closure-rate, d*r*/*r* d*t*, *in a hole at various depths and temperatures.*

maximum tolerable hole closure, e.g. because it depends on the degree of sharpening of the non-vertical edges of the cutters in contact with the hole wall. But experience shows that a considerable length of drilling time is available at shallow depths in cold ice.

The curves in Figure 2 show the strain closure-rate $\dot{\epsilon} = \mathrm{d}r/r\,\mathrm{d}t$ of a hole at various temperatures and depths. The curves are based on measurements of first-year closure of the holes at Byrd Station, Antarctica, and Site 2, Greenland, and $\dot{\epsilon}$ has been expressed as $A\sigma^n \exp(-E/RT)$, A and n being constants, σ the stress, E the activation energy (83 kJ/mol), R the gas constant, and T the (absolute) temperature (Gow, 1963).

During the drill test at Dye 2, where the ice temperature is −17°C, 100 m depth was reached in 4 d. The drill could easily pass the 80 m level 24 h after reaching this depth, i.e. according to Figure 2, an 0.003 mm hole closure caused no troubles. At −30°C the drill should therefore be able to reach at least 140 m, assuming the operation to be completed within 24 h. The time t needed to reach depth x in a continuous operation can be calculated at

$$t = \frac{t_c + t_g}{L}\,x + \frac{1}{vL}\,x^2,$$

t_c being the time needed to cut a length L of core per run, t_g the ground time spent each run at the surface for maintenance, and v the hoisting and lowering speed of the drill. With $L = 1$ m per run, $t_c = 2$ min, $t_g = 5$ min, and $v = 1\ \mathrm{m\,s^{-1}}$, a depth $x = 140$ m can be reached in $t = 24$ h.

Experiences with other drill designs suggest that the above estimate on the maximum depth is conservative. Nevertheless, further penetration may call for enlargement of the hole

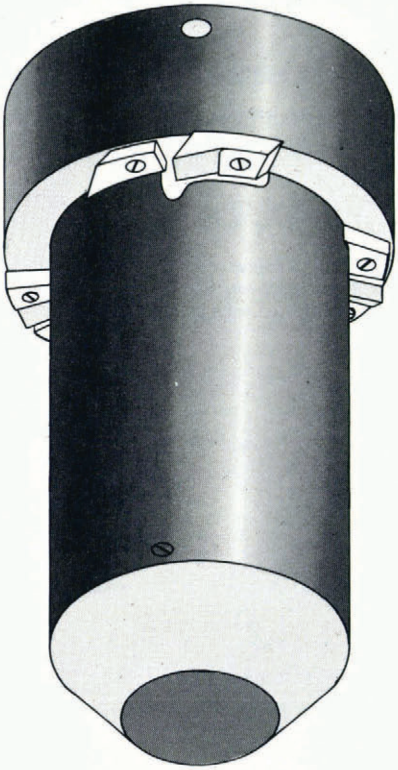

Fig. 3. Milling device for enlarging the diameter of a bore hole. Chips cut by the knives under the wide cylinder are collected in the narrow one that fits into the hole made by the shallow drill.

diameter, e.g. by the simple but highly efficient milling device shown in Figure 3. It consists of a 2 m long cylindrical container with a diameter slightly smaller than that of the drill hole. The chips cut by the knives in the top piece are collected in the cylinder.

In the summer of 1978, the milling device was attached to the motor-gear section of the drill, replacing the core barrels, and used to enlarge a 103.5 mm hole to a diameter of 135 mm down to 90 m depth, 2 m per run (milling time 2 min). The milling device could easily be modified to widen the hole diameter by, e.g. 4 mm over 20 m per run, which would allow further penetration by the core drill without any risk of sticking in the enlarged part of the hole.

By alternating use of the drill and the milling device, it is probably feasible to reach several hundred metres depth in ice colder than −20°C, but we have not felt tempted to prove this statement in practice.

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