UNIVERSITY OF MINNESOTA ICE DRILL

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ABSTRACT

The University of Minnesota ice drill is an electrically-powered, portable, thermal drill designed for boring and coring to depths of a few hundred meters in polar glaciers. A new hot-point design is used in which a cylindrical tip makes an initial hole, and a parabolic section enlarges this hole to the desired diameter. Meltwater produced is diluted with ethylene glycol and left in the hole to counterbalance the hydrostatic pressure in the ice, and thus inhibit hole closure.

Introduction

In the spring of 1974 a drill for use in cold glacier ice was designed and built at the University of Minnesota. This drill (Figs. 1 and 2) consists of an electrical system including generator, variac, transformer, cable, and hot-point or core barrel; and an ethylene-glycol system including glycol reservoir, meter, pump, and tubing. Glycol is injected immediately above the hot-point to prevent refreezing of meltwater when drilling in cold ice.

The complete drill with 5-cm and 9-cm-diameter hot-points, 9-cm core barrel, and 5-kW generator can be built for approximately $7000 and weighs about 500 kg, excluding fuel and glycol. In field tests penetration rates were between 7.6 and 8.2 m/hr with the 5-cm hot-point and about 4.9 m/hr with the 9-cm hot-point.

Most components of the drill warrant only brief description, as there is nothing unique in their design. Two elements, however, are somewhat novel, and these will be treated in greater detail. One is a switch which signals the operator to let out more cable, and the other is the hot-point.

Electrical System

Power for the drill is provided by a 5-kW gasoline-powered Onan model 5CCK generator with 120- and 240-V outlets. Power from one of the 240-V outlets is run to a Superior Electric Co. model 236BU-2 powerstat, and thence through a step-up transformer which doubles the voltage (Fig. 3). With the use of the powerstat the voltage at the control-box outlet can be varied continuously from zero to approximately 560 V. High voltages are desirable to minimize power

Figure 1. Photograph of drill in operation, June 1974. The control box and cable reel are on the nearer sled, along with a box for tools and spare parts. The generator is on the further sled; a fuel drum and pump stand behind the generator.

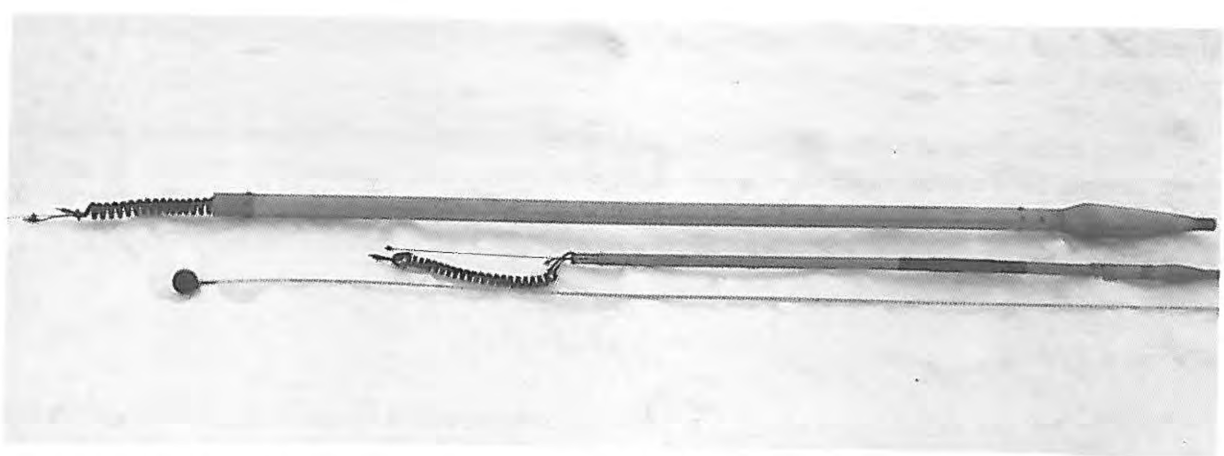

Figure 2. Hot-points and buoyancy sections. Coiled cable and switch wire are at top of buoyancy sections. Black area on buoyancy section for 5-cm hot-point is location of an emergency field repair job. Tape is 2 m long.

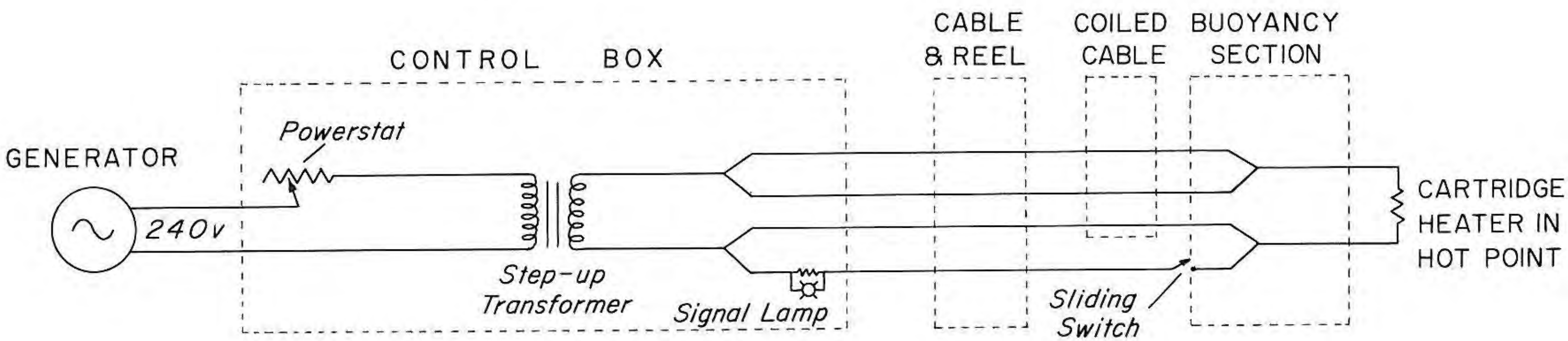

Figure 3. Schematic diagram of electrical system showing circuit for sliding switch.

losses in the cable. A flexible neoprene-jacketed type SO PWC cable with four No. 16 conductors is used to carry the power from the control box to the hand-operated cable reel, via a set of four slip rings, and thence down the hole to the hot-point. Allowable carrying capacity of this cable is 7 amperes per conductor.

The submerged part of the drill consists of a brass or copper hot-point or core barrel, and a buoyancy section (Fig. 2). The length of the buoyancy section is adjusted so that when submerged with the hot-point attached, it will assume a vertical attitude and thus keep the hole plumb (Aamot, 1968). To transfer power from the cable to the hot-point, three of the four conductors are connected to a short length of coiled 2- or 3-conductor cable (Figs. 2 and 3). One of these three leads is grounded to the buoyancy section and hence to the hot-point. The other two leads are joined and fed into the buoyancy section through an XSA-BC insulated, water-tight feed-thru, manufactured by Brantner & Associates, Inc., 3462 Hancock Avenue, San Diego, California. An insulated wire inside the buoyancy section, a second feed-thru at the lower end of the buoyancy section, and a third feed-thru on the hot-point (Fig. 4), with a wire between the latter two feed-thrus, completes this side of the circuit.

Switch

One of the four conductors in the main cable has not yet been accounted for. This conductor is connected to the upper end of a length of stiff, straight, springy wire, about 1 m long, which is clamped securely to the main cable. The lower end of this wire slides down into a 4-mm I.D. stainless-steel tube passing entirely through the buoyancy section from one end to the other. A cylindrical brass sleeve with rounded tip is slipped over the end of the wire and silver-soldered in place. This sleeve makes electrical contact with the tube and hence with the buoyancy section. When retracted from the stainless-steel tube, the sleeve enters a short thick-walled leucite tube and electrical contact is broken. The inside diameter of the leucite tube decreases at the top so the brass sleeve cannot be fully withdrawn. When the drill is being raised the weight of the hot-point is borne by the wire, the brass sleeve, and the leucite tube. Thus to provide additional strength at this point, the leucite tube is itself encased in a stainless-steel sleeve, which, however, does not make contact with the wire or brass sleeve.

When in operation, the cable is held fixed while the hot-point and buoyancy section penetrate into the ice. The coiled cable stretches, and the buoyancy section slides down the wire until the brass sleeve is retracted into the leucite tube. Current then ceases to flow in this conductor, but power still reaches the hot-point through the lead in the coiled cable which is grounded to the buoyancy section (Fig. 3).

As long as current flows through this switch, the voltage drop across a 1-ohm resistor lights a signal lamp on the control box (Fig. 3). When the brass sleeve is retracted into the leucite tube, however, the circuit is broken and the lamp goes out, at which time the alert operator lets out more cable.

Hot-Point

There appear to be two basic concepts in hot-point design. In one, used by the University of Washington (P.L. Taylor, written communication, 1974), a cylindrical cartridge heater is inserted into a hole in a solid copper cylinder. The curved surface and upper end of this cylinder are insulated to inhibit loss of heat radially and upward. Heat, therefore, is conducted downward to the lower end of the cylinder where melting occurs.

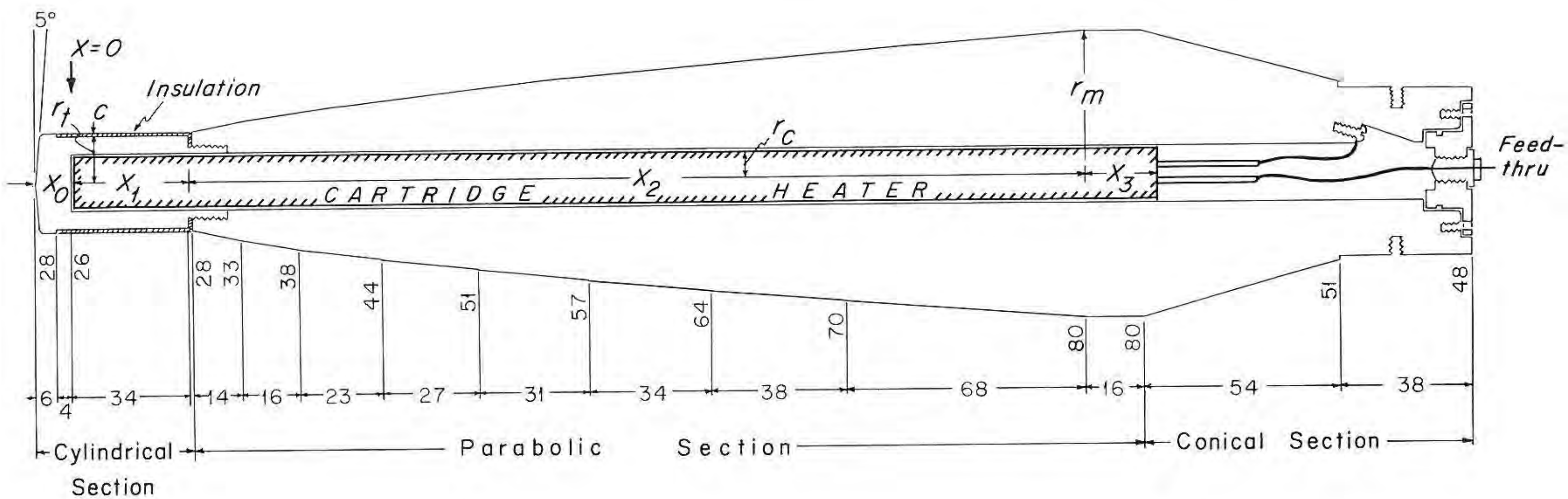

Figure 4. Cross section of 9-cm hot-point showing diameter of point at various positions, distances between these positions, insulation on cylindrical section, and definitions of variables used in calculations. All dimensions in millimeters.

In a second concept (Kasser, 1960) the hot-point is axially symmetric, say about the x-axis, and has a parabolic surface profile, $r \propto \sqrt{x}$, where r is the radius at a distance x from the tip. Heat is conducted radially outward to this surface, where melting occurs. The shape of the parabola is designed to satisfy the condition that each section of length Δx have just the melting capacity necessary to melt the ice encountered as the hot-point penetrates the ice at a uniform velocity. For a line heat source of length X located along the x-axis this condition is satisfied if r is given by·

$$r = \sqrt{\frac{x}{X}}\, r_m \qquad \text{Eq. (1)}$$

where r_m is the maximum diameter of the hot-point.

In hot-points which utilize a cylindrical cartridge heater as a heat source, the parabolic profile cannot be used at the tip because the radius of the tip must exceed that of the cartridge heater, and r, therefore, cannot decrease to zero at $x = 0$ (Eq. (1)). However, the parabolic design has two advantages over the cylindrical design. Firstly, in the parabolic design temperatures in the hot-point are substantially lower, thus reducing the possibility of failure of the heater. Secondly, construction is simpler because of the lower temperatures and because insulation is not required to prevent radial heat loss.

The present hot-point incorporates aspects of both designs. At the tip there is a cylindrical section in which radial heat loss is inhibited by insulation (Fig. 4). Heat is thus conducted downward and makes an initial hole. Above the cylindrical section there is a parabolic section in which heat is conducted radially outward and used to enlarge the hole. Finally, there is a conical section in which the diameter of the point is reduced to the diameter of the buoyancy section. It seemed advisable to make the buoyancy section somewhat smaller in diameter than the hole, lest some refreezing occur on the hole walls. As long as the buoyancy section remains free, heat lost through the conical section can be used to back out the hot-point.

The maximum temperature in the hot-point occurs immediately below the junction between the cylindrical and parabolic sections. This high temperature provides the temperature gradient down which heat is conducted to the tip. Heat loss back up into the parabolic section is inhibited by means of a rubber or teflon washer between the two sections (Fig. 4).

In order to select dimensions for the various sections such that the temperature at this junction is kept to a minimum, the temperature distribution in the cylindrical section was calculated under the assumption that radial temperature gradients are negligible. The temperature at the bottom of the cartridge heater (at $x = 0$ in Fig. 4) is given by:

$$T_0 = H\frac{x_1}{X}\,\frac{1}{\pi\eta r_t^2 K_c}\sinh(\eta x_0) + T_b \qquad \text{Eq. (2)}$$

where H is the total heat generation by the cartridge heater in cal/sec, x_0 is the distance from the bottom of the cartridge heater to the blunt tip of the hot-point, x_1 is the length of the part of the cartridge heater which is in the cylindrical section, r_t is the radius of the cylindrical section, K_c is the thermal conductivity of the metal, T_b is the temperature at the ice-metal boundary, and $\eta = \sqrt{2\frac{K_i}{cK_c r_t}}$ where c is the thickness of the insulation around the cylindrical section and K_i is the thermal conductivity of this insulation. The temperature at the junction between the cylindrical and parabolic sections is then obtained by numerically integrating the equation:

$$\frac{d^2T}{dx^2} - \eta'^2 T + \xi = 0 \qquad \text{Eq. (3)}$$

over the interval $x = 0$ to $x = x_1$, using the boundary condition $T = T_0$ at $x = 0$. In this equation $\eta' = \sqrt{2 \frac{K_i}{cK_c} \frac{r_t}{(r_t^2 - r_c^2)}}$ where r_c is the radius of the cartridge heater, and $\xi = \frac{H}{\pi X K_c (r_t^2 - r_c^2)}$.

The shape of the parabolic section is now given by:

$$r = \sqrt{(r_t + c)^2 + \frac{x - x_1}{X} r_m^2} \qquad \text{Eq. (4)}$$

The term involving η' in Eq. (3) represents the effect of radial heat loss through the insulation. A similar term involving η appeared in the differential equation from which Eq. (2) was obtained by integration. This heat loss is:

$$H_l = H \frac{x_1}{X} (\cosh (\eta x_0) - 1) + \int_0^{x_1} K_1 \frac{T}{c} 2\pi r_t \, dx \qquad \text{Eq. (5)}$$

The term involving ξ in Eq. (3) represents the effect of the heat source—the cartridge heater.

In order to transfer heat from one medium (say brass) to another medium which is in contact with the first (in this case water or ice), there must be a temperature difference, ΔT, between the two media. This temperature difference is proportional to the heat flux, q, thus:

$$\Delta T = \frac{q}{a}$$

where a is a coefficient of heat transfer.

Kasser (1960) notes that heat transfer from metal to ice is about three times as intensive as from metal to water. This is significant because heat is thus preferentially drawn to places where the hot-point is in contact with ice, and these are precisely the points where heat is required at any particular instant. However, the coefficient of heat transfer at a particular point may vary with time depending on whether the hot-point is in contact with water or with ice. Furthermore, if the hot-point is in contact with ice, the coefficient of heat transfer also depends upon the pressure at the contact point. Thus accurate calculation of ΔT is impossible, and the boundary temperature, T_b, cannot be determined theoretically.

In an attempt to measure T_b, five thermistors were embedded in the 9-cm hot-point. Leads to the thermistors were run down the outside of the hot-point, so this side of the point could not be in contact with ice during the experiment. Because heat transfer to water is less efficient, as noted, measured temperatures are expected to be somewhat higher than under actual operating conditions. In general, measured temperatures were 50 to 65°C higher than temperatures calculated on the assumption $T_b = 0$. Thus under normal operating conditions when the hot-point is largely in contact with ice it is estimated that T_b is approximately 20 to 30°C if H/X is 34 cal/cm sec.

Once the length and radius of the cylindrical section are selected, attention is directed to the conical section. Part of the cartridge heater extends into this section to provide heat for back out if necessary. During drilling this heat is transferred to the water and eventually either melts more ice, thus enlarging the hole, or is lost to the glacier. As the efficiency of this section is lower than that of the other two, its length should be kept relatively short. Regardless of its length, however, ice is melted by the heat generated in it, and the most efficient design is one which utilizes this heat to enlarge the hole to the desired diameter, rather than wasting the heat by making the hole larger than necessary. Thus the maximum diameter of the point is somewhat less than the design diameter of the hole.

On the basis of these several considerations, two hot-points were designed and built. The dimensions of the points are given in Table 1. The larger point was built first, tested in the laboratory, and then modified in accordance with the tests. The tests provided a basis for estimating the relative efficiencies of the three sections and these efficiencies were taken into consideration in the modifications. The small point was designed using these same relative efficiencies. However, in field tests of this point, the fall in water level in the hole as the hot-point was withdrawn suggested that the actual hole diameter was about 0.8 cm larger than design. This is interpreted as indicating that the efficiency of the cylindrical section was lower on the smaller point, probably because of the substantially lower pressure of the point against the ice.

It will be noted in Table 1 that the small point was designed for only 2000 W. Unfortunately the manufacturer of the cartridge heaters (Hotwatt, Inc., 128 Maple Street, Danvers, Massachusetts) could not supply higher-powered heaters that were sufficiently small in diameter to use in this small a point. This consideration, and the fact that the cylindrical section is more than one-quarter of the length of the point, suggest that the present design is not practical for hot-points less than 5 cm in diameter.

Calculated heat losses and maximum temperatures in the cylindrical section are also given in Table 1. The calculated value of H_l for the large point agreed well with estimates of the actual heat loss based on laboratory measurements. It also appeared that calculated values of T_{max} were at least qualitatively correct because rubber insulation was quite satisfactory on the cylindrical section of the large point, but burned up when used on the small point, indicating that the latter was substantially hotter, as predicted.

The overall efficiencies given in Table 1 are based on the ratio of the power required to melt ice which was initially at about -8^{o}C, to the total power expended in the point. Line losses, which amounted to about 10 per cent of the total, are not included. The higher efficiency of the small point reflects its higher penetration rate, and hence the shorter time available for loss of heat by conduction to the ice surrounding the hole.

Core Barrel

A core barrel designed to be interchangeable with the 9-cm hot-point was built during the Spring of 1975. The barrel fits on the bottom of the buoyancy section, and takes a 50-cm core. We intend to take core every 5 or 10 m during drilling.

The barrel is modeled after that developed by the University of Washington (P.L. Taylor, written communication, 1974) and described elsewhere in this publication.

Table 1

Dimensions and Design Characteristics of Hot-Points

Point	Design hole diameter, cm	Actual hole diameter, cm	x_o, cm	x_1, cm	r_t, cm	c, cm	x_2, cm	x_3, cm	r_c, cm	r_m, cm	Design power, watts	Design current, amperes	H_l, cal/sec	Calculated T_{max}, ^oC*
Small	4.5	∿ 5.3	1.0	2.9	1.0	0.1	6.6	0.7	0.6	2.0	2000	9.1	9.8	143
Large	8.9	∿ 9.0	1.0	3.4	1.3	0.1	25.1	1.9	0.8	4.0	4400	9.8	8.7	84

Point	Point Material	Insulating Material	Weight, kg	Estimated Efficiency, %	Penetration rate, m/hr
Small	Copper	Teflon tape	1.0	85	7.6 - 8.2
Large	Copper for cylindrical section Brass for rest	Rubber (bicycle tube)	8.7	75	4.9

*Assuming $T_b = 0$.

Glycol System

In polar glaciers with temperatures between 0 and about -15°C, hole closure can be a problem at depths of a few hundred meters if the hydrostatic pressure in the ice is not balanced by a comparable pressure in the borehole (Weertman, 1973). Therefore in the present system meltwater produced by the hot-point is diluted with ethylene glycol and left in the hole.

The glycol system consists of a reservoir, made from a 10-gal drum, whence glycol is drawn by a hand-operated piston pump and forced down the borehole through 0.96-cm I.D. plastic tubing. Between the reservoir and the pump there is a filter to remove foreign particles from the glycol, and, initially, a meter which recorded the total volume of glycol injected. The meter proved to be unsatisfactory as the glycol did not lubricate it properly. In its place a transparent tube and centimeter scale were installed on the side of the 10-gal drum to monitor glycol use.

The pump used is a piston pump designed by Kasser (1960) and capable of developing pressures of 5 to 10 kg/cm^2.

The plastic tubing used was black poly-flo tubing manufactured by Imperial Eastman Company, Chicago. Imperial Eastman also manufactures a variety of fittings which can be used with this tubing. The tubing is taped to the electrical cable, and both are handled simultaneously on the cable reel. The connection to the reel is made by means of a quick-release fitting on the hollow axle of the drum. This fitting doubles as a swivel coupling, although not actually designed as such. This cable system has proved to be awkward, however, due to differences in the coefficients of thermal expansion of the cable and tubing, and perhaps also to plastic stretching of the tubing. Alternatives are presently being investigated.

At the top of the buoyancy section a piece of latex surgical tubing, about 1 m long, is used to connect the plastic tubing to a 4-mm I.D. stainless-steel tube which passes entirely through the buoyancy section. This tube is parallel to the tube mentioned earlier for the switch. The surgical tubing is sufficiently elastic to stretch, along with the coiled electrical cable, as the hot-point penetrates into the ice. The glycol is thus injected immediately above the hot-point at the junction between the point and the buoyancy section.

When the drill is in operation, the reading on the glycol meter and the hole depth are recorded frequently, and the pumping rate is adjusted so that the concentration of glycol in the hole is just sufficient to prevent freezing at prevailing ice temperatures. The volume of glycol injected per meter of hole drilled will obviously depend upon hole diameter and ice temperature. The pump capacity should be such that this volume can be injected by an operator pumping at a leisurely rate 10 to 25 per cent of the time.

Concluding Statement

The drill was used on the Barnes Ice Cap, Baffin Island, N.W.T., in June and July 1974 and June 1975. Three 5-cm-diameter holes were drilled to the bed of the glacier at points near the margin where the ice was 100, 110, and 132 m thick respectively. These holes were cased with 3-cm O.D. aluminum casing and filled with diesel fuel. Temperature measurements were obtained in the two shorter holes.

A fourth hole was drilled to a depth of 43 m with the 9-cm hot-point in 1974. Penetration ceased at this depth due to an accumulation of sediment in the bottom of the hole. In 1975 a fifth hole was drilled near the fourth. Dirty ice was again encountered at a depth of 41 m, but with the use of the core barrel built in 1975 we were able to penetrate an additional 11.5 m of this dirty ice before drilling rates became unreasonably low (<0.1 m/hr). Both temperature and inclinometer measurements were obtained in this hole, and fabric studies have been completed on cores from it.

On the basis of our experience during the 1974 field season, there is no reason to believe that the drill will not be suitable for drilling to the design depth of 450 m, though considerable patience may be required for the deeper holes.

Acknowledgments

I would like to thank Lyle Hansen for providing the impetus for development of this drill, Philip Taylor for sharing with me his ideas on drill design, the National Science Foundation (Grants GA-19310 and GA-42728) for financial support, and the Glaciology Division, Department of Environment, Canada, for logistical support in the field.

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