A LIGHT-WEIGHT HOT WATER DRILL FOR LARGE DEPTH : EXPERIENCES WITH DRILLING ON JAKOBSHAVNS GLACIER, GREENLAND

by

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ABSTRACT

Near the centerline of Jakobshavns Glacier, at a distance of 45 km from the calving front, 4 holes were drilled to 1200 m - 1330 m depth, each taking 12 to 18 hours to drill. A few shallow holes were also drilled. Original diameters of the deep holes ranged from 120 mm to 180 mm depending on drill speed. Boreholes froze at a fast rate, e.g. a hole with a diameter of approximately 180 mm froze shut in less than 10 hours. Thermistors were installed in several holes and the temperature adjustment was recorded. The ice temperature decreases almost linearly from -18°C at 400 m to -22°C at 1000 m depth.

The hot water drill consisted of a 6 m long drill stem with a diameter of 30 mm and 3/4 inch medium-pressure hose. The drill speed was controlled by a capstantype motor winch. A water discharge of 3.6 m^3/h was provided by 3 piston pumps, the water was heated to 58 - 76°C by three to four diesel oil heating units.

INTRODUCTION

Jakobshavns Glacier flows with continuously high speed ; it is the fastest ice stream of this type. The dynamics of Jakobshavns Glacier have been studied in detail by the University of Alaska (Echelmeyer and Harrison, 1988). Further investigation of the mechanism for fast flow of this glacier requires knowledge of the conditions at the base and in the interior of the ice. Therefore, a joint deep-drilling project (University of Alaska and Federal Institute of Technology (ETH) Zürich) has been developed for 1988 and 1989. Preliminary results from the 1988 season are described in this paper.

Holes in ice can be drilled at a fast rate with a hot water drill. This method has been used by numerous investigators. References - to quote a few - are : Reynaud and Courdouan, 1962 ; Gillet, 1975 ; Iken et al., 1977 ; Napoléoni and Clarke, 1978 ; Hodge, 1979 ; Röthlisberger, 1980 ; Hantz and Lliboutry, 1983 ; Clarke et al., 1984 ; Haeberli and Fisch, 1984 ; Koci, 1984 ; Taylor, 1984 ; Kamb et al., 1985 ; Blatter, 1987 ; Hooke et al., 1987 ; Engelhardt and Determann, 1987 ; Rado et al., 1987. Recently, a hot water drill has been used successfully to drill to a large depth, 970 m, in the fast moving Columbia Glacier (Kamb and Engelhardt, personal communication).. As the depth is increased the cooling of the hot water on its way through the drilling hose becomes an increasingly important concern. For the present operation, a drill with a depth range of 1600 m was assembled.

The 1988 drill site was chosen on the center line of the ice stream, at a distance of 45 km from the calving front (Fig. 1). At this drill site the velocity is very high (1.1 km/yr) but the ice is not highly crevassed. Melt water streams provide a convenient water supply for the drill. A pilot study of numerous single seismic shots distributed over a large area in 1986 indicated reflections from a distance of 1300 to 1400 m near the drill site. However, more detailed seismic investigations, carried out along with the drilling in 1988, revealed an ice depth of 2500 m at this site (Clarke and Echelmeyer, 1988).

The ice temperature decreases linearly from -18°C at 400 m depth to -22°C at 1000 m depth. This is much colder than has been assumed in models of ice flow and temperature so far, based on shallower depth and slower velocity (Radok et al., 1982).

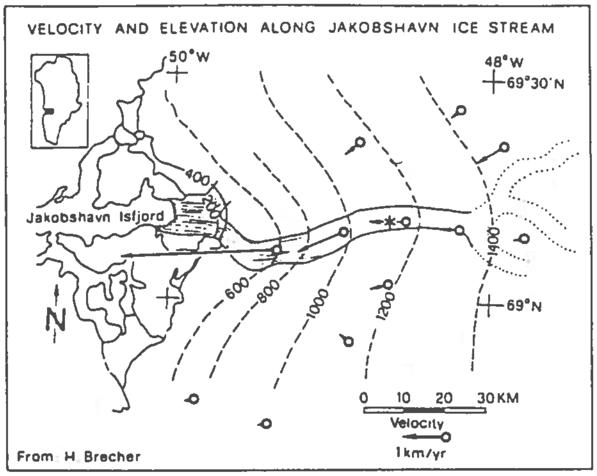


Fig. 1 - Jakobshavns Glacier. The location of the drill site is indicated by an asterix.

REQUIREMENTS FOR DRILLING TO LARGE DEPTH

A hot water drill has a limitation of its depth range : the limit is reached when the hot water flowing through the drill-hose cools to the freezing point by the time it arrives at the drill tip. The water temperature, ϑ, decreases exponentially with depth, L :

$$\vartheta(L) = \vartheta_0 \, e^{-\frac{L}{Q c_w R}} \qquad (1)$$

where

ϑ_0	is the temperature at depth L = 0 (at the hole entrance)
Q	is the discharge of water
C_W	is the heat capacity of water per unit volume
R	is the effective thermal resistance to radial heat flow

Cooling of the hot water with increasing depth can be counteracted, as eq. (1) shows, by either increasing the insulation of the hose (thereby increasing R) or by increasing the discharge. Increasing the discharge serves not only to maintain a high water temperature at depth but also directly increases the rate of energy output. The drilling rate, dL/dt is proportional to this rate of energy output :

$$\frac{dL}{dt} = C^* c_W Q \quad \vartheta(L) \qquad (2)$$

C^*, the specific drilling rate, depends on the nozzle diameter d (Iken, 1988) and, weakly, on the ice temperature. A semi-empirical relation is

$$C^* = \frac{A_0}{d^2 \left(H_v + c_i \; |\vartheta_i| \right)^{1/3}} \qquad (3)$$

where

A_0 = 7.904 x $10^{-7} m^2 \, kcal^{-2/3}$

= 7.15 x $10^{-5} m^2 \, kWh^{-2/3}$

d = nozzle diameter (m)

H_v = latent heat of ice (per unit volume)

c_i = heat capacity of ice (per unit volume)

ϑ_i = ice temperature (°C)

In order to maintain a large discharge at great depth, either the pressure of the pump or, more effectively, the inner diameter of the hose must be maximized. For a long length of hose the square of the discharge is essentially proportional to the 5th power of the inner diameter of the hose.

CHOICE OF EQUIPMENT

A light-weight drill which would be easy to transport and to operate and which would be capable of drilling to a depth of 1600 m, was required for this project. Cost had to be kept to a minimum and existing equipment, such as pumps and heaters, was to be integrated into the new drilling system.

In view of the considerations in the previous pararaph a hose with a relatively large inner diameter was chosen, namely a commercial 3/4" (19 mm inner diameter) medium-pressure hose designed for a working pressure of 88 bars. This hose is flexible enough for easy handling during the operation.

Spools, carrying this size of hose would have been quite heavy and bulky. Therefore a capstan-type motor winch was used to lower or lift the hose during drilling. The wheel of the winch was equipped with a groove for increased friction (Fig. 2). The hose was wound around this wheel for 3/4 of a turn as shown in figs. 2 and 3. With this set-up a small braking force suffices to prevent slipping of the hose on the wheel. The ratio of braking force F and weight W is given by

$$\frac{F}{W} = \exp\left[\frac{3}{4} (2 \pi \mu) / \sin \frac{\alpha}{2}\right]$$

where

μ is the coefficient of friction between hose and wheel

α = 45° is the angle of the groove.

(This equation is derived in mechanics text books (e.g. Hütte, 1971, p. 54)).

Hose sections of 100 - 200 m length were added as the drill proceeded down the hole : they were coiled up in the shape of a figure 8 on a tarp. Three piston pumps in parallel provided a total discharge of 3.6 m^3/h of water which was heated to 58 - 76°C by three to four diesel oil heating units. The 6 m long drill stem with an outer diameter of 30 mm consisted of three screwed-together sections of double-walled, lead-filled tubes. Nozzles of different sizes could be attached at the end of the 300 mm long conical drill

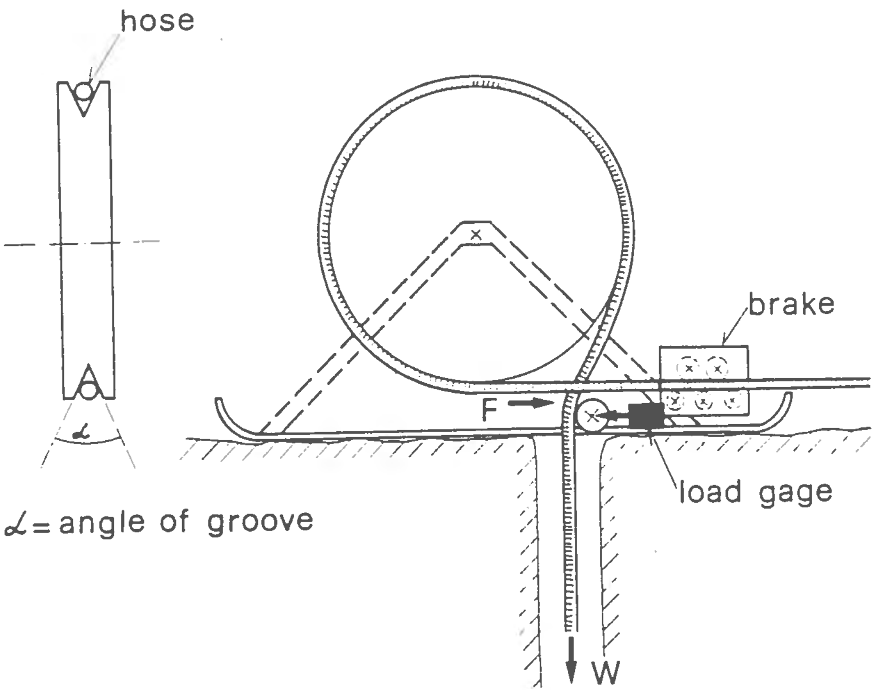


Fig. 2 - Scheme of winch.

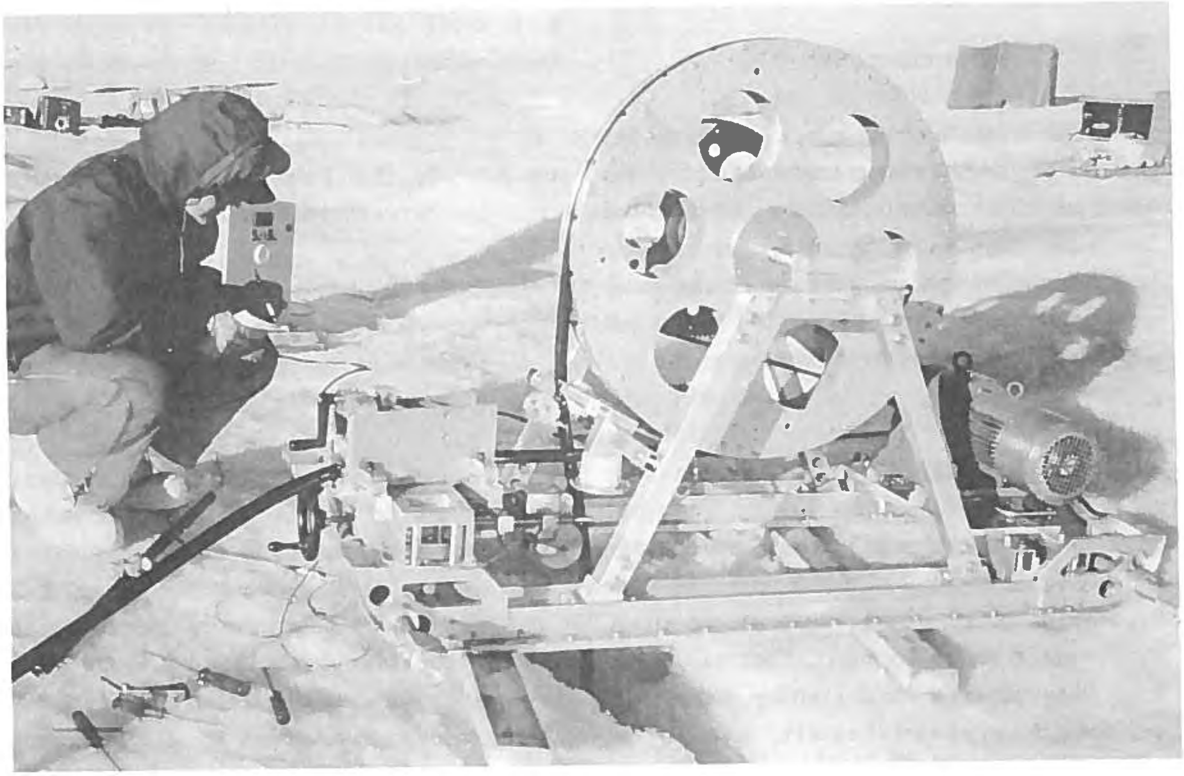


Fig. 3 - The winch during operation (photo taken by P. Gnos).

tip. The total weight of the equipment (with water tank and generators) is 1000 kg plus 30 kg/100 m hose. The heaviest piece is the motor winch on a sled (180 kg).

CONTROL OF DRILL SPEED AND HOLE SIZE

In order to drill a vertical and uniform hole the speed of the winch feeding the hose into the hole must be reduced as the drill proceeds. The appropriate drill speed at a given depth can be inferred from the water temperature at the drill tip or from an effective value of the thermal resistance to radial heat flow, R. We have estimated the latter by means of a test run at maximum drill speed. In this test, discharge and water temperature at the borehole entrance were kept constant and the drill was lowered by hand at a speed slightly slower than that at which vibration of the drill stem occured. (When the drill tip almost touches the bottom of the hole the drill starts to vibrate). The depth of the drill as a function of time during this test run is shown in Fig. 4. The slope of this curve at different depths is used to draw line 2 in Fig. 5. From the slope of line 2 an approximate value of R can be calculated by equations 1 and 2 ; the result is R = 0.31 ± 0.04 h m deg/kcal. The logarithm of the drill speed is a linear function of depth if R and C^* are constant (eqs. (1) and (2)). R is the sum of the thermal resistance of the hose and of the thermal resistance of the water layer surrounding it. The latter depends on the hole radius, the discharge through the hole and on the position of the hose in the hole (the hose need not be in the center of the hole). The value determined for R is therefore only an approximation. The effect of the variation in C^* with ice temperature is small in this model.

Graphs similar to Fig. 5 were used for adjusting the drill speed as the depth of the borehole increased. For example : if a borehole with twice the cross-section of the test hole is to be drilled, the drill speed is set to half the speed used in the test run ; this case is indicated by line 4 in Fig. 5. Maximum drill speeds obtained using different water temperatures or discharges are depicted by lines 1 and 3, respectively. These examples refer to a nozzle with 4 mm diameter. Alternatively, line 1 can be interpreted as the maximum drill speed at $\vartheta_0 = 50°C$, $Q = 3.6\ m^3/h$ and a nozzle diameter of

$$d = 4 \sqrt{\frac{59}{79}} = 3.46 \text{ mm.}$$

The time required to drill to a certain depth can be inferred by integration of eq. 2. For instance, 10 hours are required to drill to 1300 m depth at 95 % of full speed using a 4 mm nozzle, a discharge of 3.6 m^3/h and an entrance temperature of 65°C. The actual drilling time was 13 ¼ hours due to a temporary reduction of discharge and some interruptions.

RECORDS OF APPLIED PRESSURE

In Fig. 6 the applied pressure recorded during drilling is plotted versus the length of hose. In all examples the discharge was 3.6 m^3/h (or normalized to this value). 40 m of the hose were at the surface, the remainder in the borehole. The graph suggests that the loss of pressure head per unit length of hose - or depth of hole - is influenced by the hole diameter : holes 1 and 2 had a diameter of approximately 115 mm, some 20 metres above the drill tip. These holes were drilled with a nozzle of 4 mm diameter at 95 % full speed. Hole 3 had a diameter of approximately 160 mm and was drilled with a 4.5 mm-nozzle at 65 % of full speed. Hole

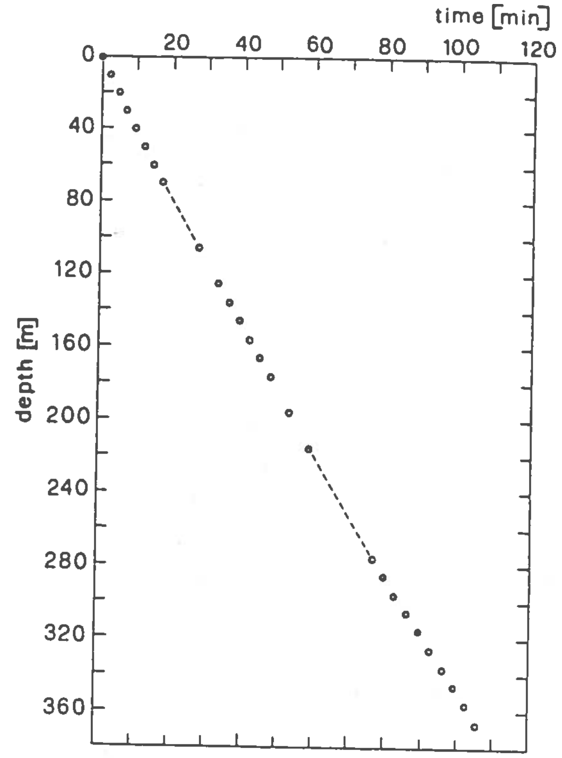


Fig. 4 - Depth of drill as a function of time in a test run. Nozzle diameter : 4 mm, discharge : 3.6 m^3/h, water temperature at heater : 65°C.

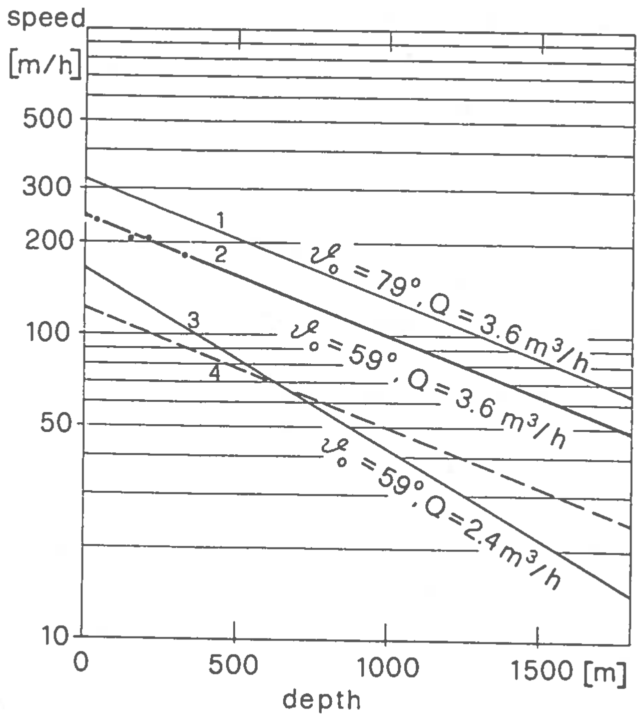


Fig. 5 - Drill speed as a function of depth assuming that R and C* are constant. Data points correspond to the slope of the curve in Fig. 4.

4 had a diameter of approximately 175 mm and was drilled with a 4.4 mm nozzle at 55 % of full speed. (The hole diameters were inferred from the supplied energy, as discussed below (eq. 4)). The temperature at the heaters was usually in the range of 66 to 74°C (the temperature was lowest in case of hole 3 and highest in case of hole 4).

The reason for the influence of hole diameter is not clear ; it is not obvious why the upward flow of water in the rather wide holes should require a significant pressure gradient. Taking into account the freezing rates of holes or the differences in insulation - the viscosity of the water in the hose depends on its temperature - does not lead to quantitatively satisfactory explanations either.

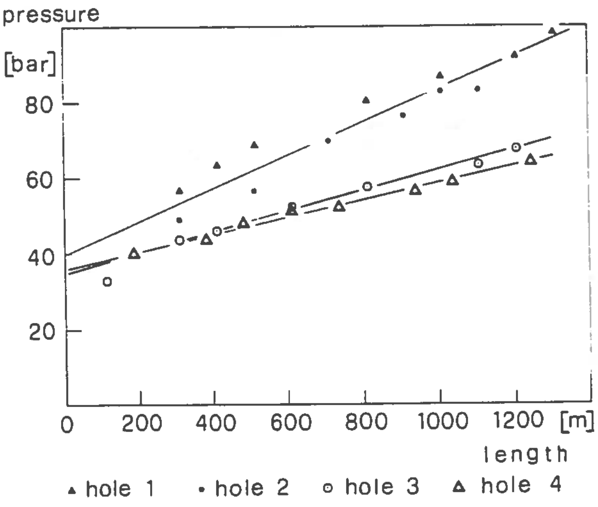


Fig. 6 - Applied pressure versus length of hose recorded during drilling with a discharge of 3.6 m^3/h. At length 0 the pressure corresponds essentially to the loss of pressure head in the nozzle. Additional information is given in the text.

ICE TEMPERATURE

Calibrated thermistors were inserted into boreholes and the temperature recovery was recorded. For example, the plot of temperature versus time in Fig. 7a indicates that the water near the thermistor froze during the first hour and that the hole froze shut within 10 hours or less. The maximum cooling rate occurs when no more liquid water is present. This thermistor was 18 m above the bottom of the hole. In Fig. 7b the temperature is plotted versus 1/time ; extrapolation suggests a final, steady temperature of approximately -21.8°C. (This type of plot is suggested by the function describing the decay of a temperature disturbance due to an instantaneous line source of heat (Carslaw and Jaeger, 1959, Par. 10.3)). Fig. 8 shows the temperature profile at the drill site. The almost linear decrease of temperature from -18°C at 400 m depth to -22°C at 1000 m depth suggests that a considerable part of the glacier is at even lower temperature. These low temperatures can lead to rapid closure of the boreholes.

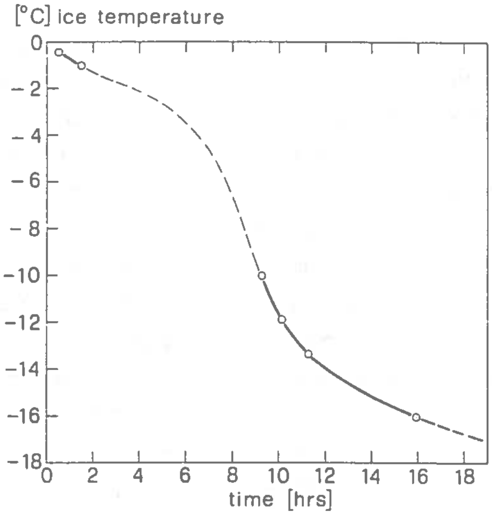
FREEZING RATES OF BORE HOLES

(a) Heat (warm hose) removed shortly after drilling

Figs. 9 and 10 are examples of the gradual freezing of boreholes measured with a caliper. Smooth lines have been drawn through the scattered data points. The line labelled r_o indicates the original hole radius which was found by extrapolation as explained below. The line labelled r_m (Figs. 9 and 10) indicates a maximum hole radius which would be obtained if all energy supplied at the drill tip were to be dissipated instantaneously at the same location.

r_m is given by :

$$r_m^2 = \frac{\vartheta_{tip}\, Q\, c_w}{\pi\, S\, (H_v + |\vartheta_i|\, c_i)} \qquad (4)$$



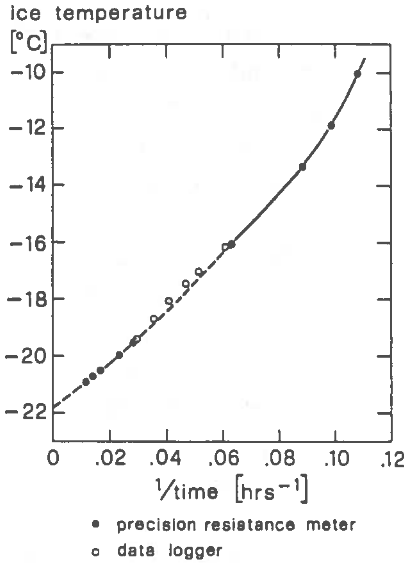


Fig. 7a - Temperature variation shortly after drilling. The thermistor is at 988 m depth. The thin, broken line sketches a typical temperature variation ; no measurements were taken during this time interval.

Fig. 7b - Temperature recovery at 988 m depth ; extrapolation suggests a final, steady temperature of - 21.8°C.

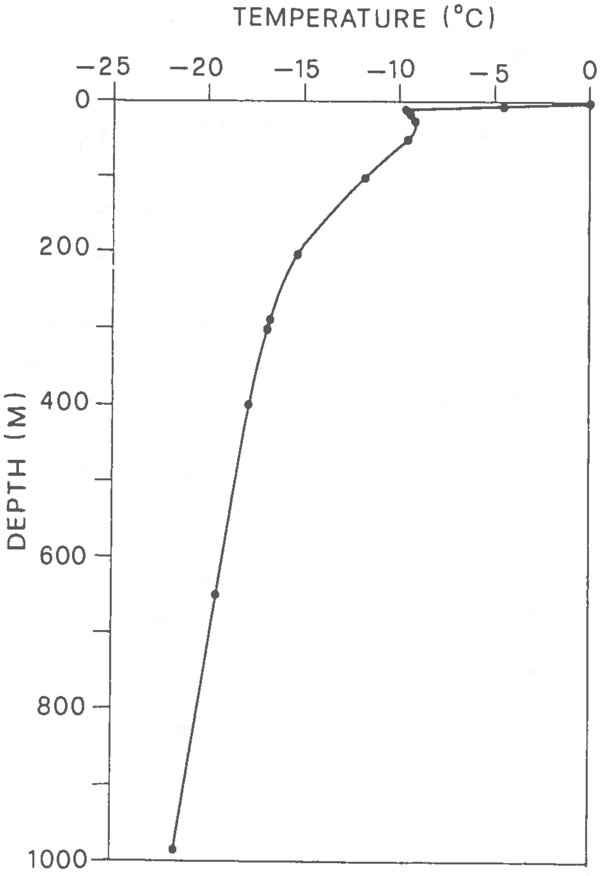


Fig. 8 - Ice temperature profile at the drill site.

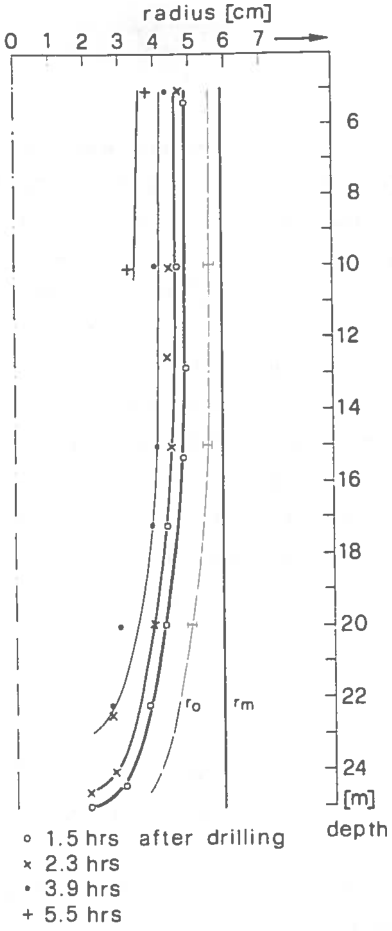


Fig. 9 - Gradual freezing of a borehole drilled to 25 m depth. Ice temperature -9.5°C.

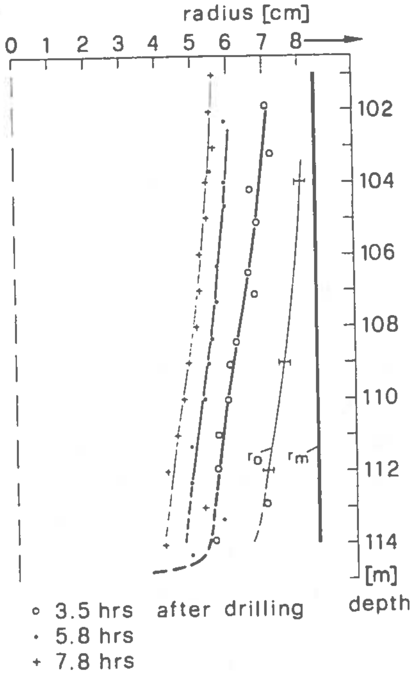


Fig. 10 - Gradual freezing of a borehole drilled to 114 m depth. Ice temperature at bottom of hole : -12°C.

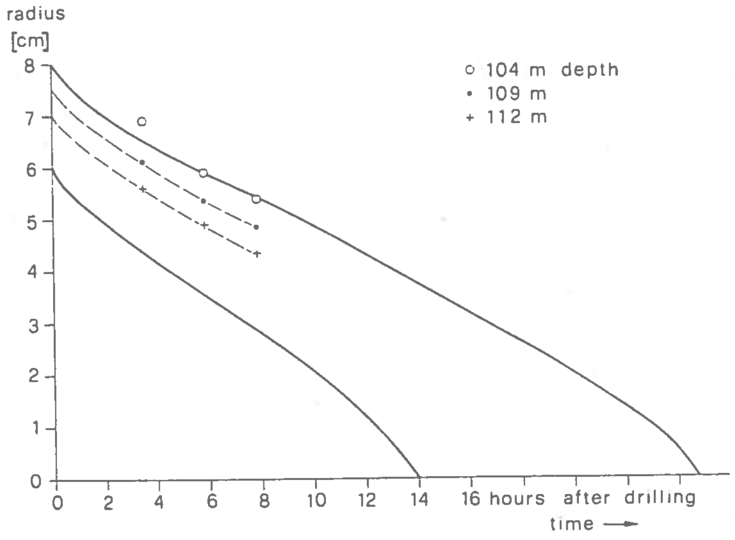


Fig. 11 - Calculated and measured freezing of boreholes at -12°C (data from Fig. 10). The calculated hole radii (fat lines) refer to initial radii r_0 = 6 and r_0 = 8 cm, respectively.

where

S is the drill speed chosen

ϑ_{tip} is the temperature of the water flowing through the nozzle

The hole shown in Fig. 9 was drilled with a 4 mm nozzle at approximately 95 % of full speed ; the hole in Fig. 10 was drilled with a 4.5 mm nozzle at 63 % of full speed. In both cases the drill was removed from the hole immediately after drilling. In Fig. 11 hole radii are plotted versus time. The heavy lines depict theoretical freezing rates obtained by numerical modelling. The points also shown in Fig. 11 are taken from the smooth curves in Fig. 10 ; they represent actual hole radii at three different times. Lines drawn through these points, parallel to the theoretical curves, indicate the original hole radii r_0 at certain depths. These values of r_0 have been inserted in Fig. 10.

The results indicate that the original hole diameter at a distance of 10 m above the drill tip amounted to approximately 90 % of the maximum possible hole diameter.

(b) Heating continued after drilling

While the drill is advancing to greater depth, heat is transferred continuously from the drill hose to the borehole wall. The heat loss from the hose per unit length amounts to ϑ / R where ϑ is the water temperature in the hose and R is the effective thermal resistance to radial heat transfer. Problems with drilling may be expected if the melting rate corresponding to the heat transfer from the hose is insufficient to balance the freezing rate of the borehole. We are investigating this problem numerically. Results are obtained by solving the heat conduction equation with a finite difference approximation taking into account the moving phase boundary and a heat source of given strength in the borehole. This study is still in progress. Two typical situations are illustrated below. In the first example, shown in Fig. 12, a relatively large heat transfer from the hose and a moderately low ice temperature are assumed. In this case the hole widens continuously until the hose is removed. The subsequent freezing of the hole is slower than it would be if there were no down-hole heating. The assumed ice temperature corresponds to a depth of 700 m at the drill site ; the heat loss from the hose, ϑ_1 / R, corresponds to ϑ / R = .31 m deg h/kcal = .074 deg/kW and to a water temperature ϑ = 47°C.

In the second example, shown in Fig. 13, a small heat transfer from the hose and a lower ice temperature, -25°C, are assumed. In this case the hole freezes, inspite of the presence of the warm hose, until its diameter is reduced to 17 % of the original value. Subsequently, the hole widens at a slow rate. This example demonstrates the need for drilling wide holes in cold ice in order to allow down-hole instrumentation before the hole closes and also to ensure that the hose does not freeze in during drilling. In Jakobshavns Glacier an ice temperature of -25°C is expected at 1450 m depth (by extrapolation of Fig. 8). The heat flow assumed corresponds to a water temperature ϑ = 21°C in the hose at that depth. The dimensionless time, t^*, is related to time t (hours) by

$$t^* = t \, \lambda \, \vartheta_1 \; / \; (H_v \; r_0^2) \qquad (5)$$

where

λ is the thermal conductivity of ice

r_0 is the initial borehole radius.

An observation made during drilling beyond 1300 m may possibly be explained by fast

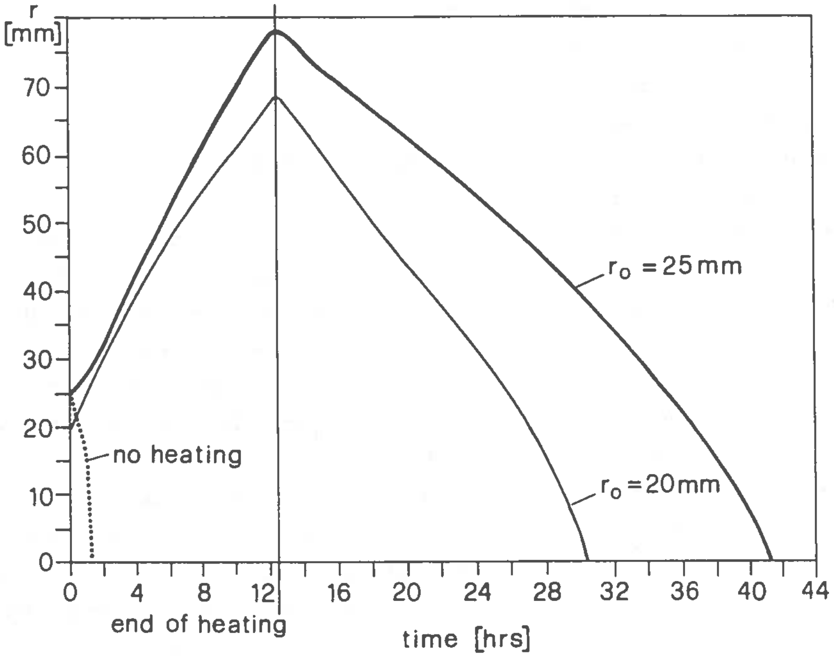


Fig. 12 - Calculated enlargement of a borehole after drilling by heat transfer from the drilling hose and subsequent freezing. Ice temperature : -20°C, assumed heat loss from hose : 150 kcal/(mh) = 174 W/m.

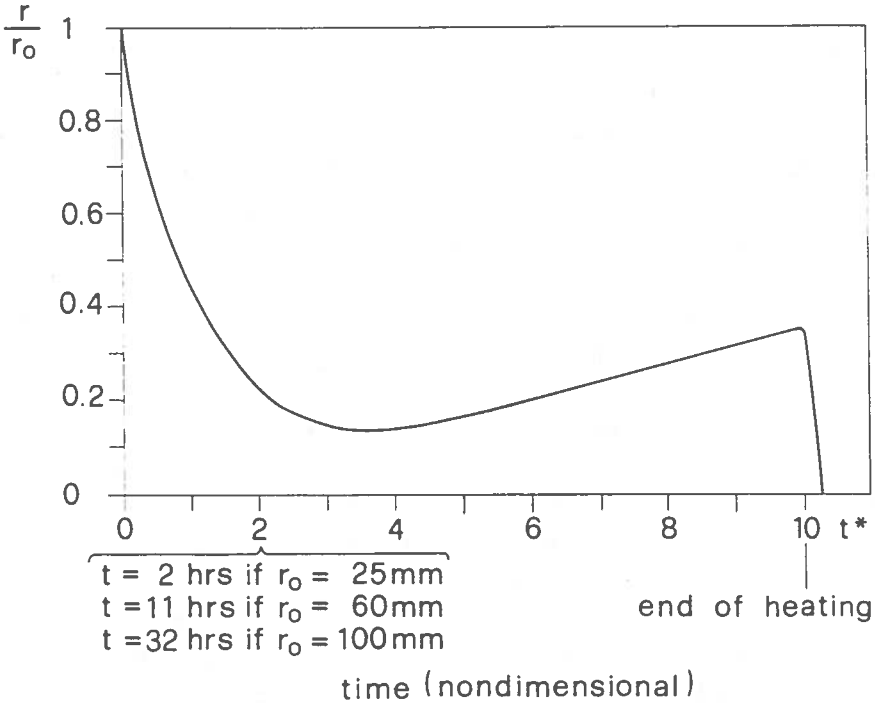


Fig. 13 - Calculated variation of hole radius due to slightly warm hose in hole. Ice temperature : -25°C, assumed heat loss from hose : 73 kcal/(mh) = 85 Watt/m.

hole closure as displayed in Fig. 13. When the drill reached about 1300 m depth, 4.5 hours after it had passed 1000 m, the weight of the hose increased at a lower rate than usual with increasing depth. It is conceivable that the hole above had narrowed sufficiently so that the drag exerted on the hose by the upward flowing water became noticeable. This hole had been drilled fast, with an original radius of only 50 to 60 mm. It was too narrow for instrumentation soon after drilling. In contrast, no difficulties where encountered when a thermistor cable with a lead weight of 30 mm in diameter attached to the end was lowered to the bottom of a 1200 m deep borehole which had an original radius of 80 to 90 mm. This hole had been drilled in 18 hours ; the hose was pulled out immediately and the thermistor was inserted 1.5 hours after completion of the hole. (This thermistor or a splice along the cable failed ; so no temperature data was obtained at this depth).

CONCLUSIONS

In spite of the unexpected low ice temperature encountered the hot water drill has proved to be a powerful tool for drilling to large depth.

The observed relationship between applied pressure and depth of a hole suggests that the full discharge of 3.6 m^3/h could be maintained to 1800 m depth, a depth that could therefore be reached in temperate ice with the present type of equipment. In the cold ice of Jakobshavns Glacier, it is necessary to drill very wide holes (at least 200 mm in diameter) when drilling to a depth of 1600 m. This condition reduces the drilling range that is practical because of the very long drilling times required. By fully utilizing the possibilities of the present equipment, in particular by increasing the entrance temperature with additional heaters, it should be possible to drill to 1600 m depth and also to reach the glacier bed in a semi-marginal location.

ACKNOWLEDGEMENTS

We wish to thank all members of the field party for their excellent cooperation and competent performance under often adverse conditions : Ted Clarke, Dawn Cosgrove, Martin Funk, Paul Gnos, Garry Holton, Stephan Wagner and Reto Wanner. P. Gnos constructed the drill stem and various special parts of the drilling system. L. Kozycki and J. Benevento constructed a caliper, an inclinometer and other measuring devices. The winch was designed by C. Bucher and constructed in the VAW-workshop, in particular by J. Steiner who also contributed valuably to the design. A prototype of the winch had been constructed by H. Rufli. C. Sidler prepared several electronic devices and equipped an inclinometer with a compass obtained from H. Engelhardt.

B. Koci, H. Rufli, H. Engelhardt, G. Oplatka, H. Röthlisberger and A. Weidick gave valuable advice on certain components of the drilling equipment. B. Kamb and P. Taylor made available to us the design of a backward spraying nozzle.

G. Zwosta typed the manuscript ; B. Nedela prepared the drawings.

Excellent logistic support was provided by the Polar Ice Coring Office, in particular by K. Swanson and his team in Sondrestromfjord.

This research was funded by grants from the US National Science Foundation and the Schweizer Nationalfonds zur Förderung der wissenschaftlichen Forschung.

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