A HOT WATER DRILL FOR TEMPERATE ICE

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Abstract

The development of a high-pressure hot-water drill is described, which has been used reliably in temperate ice to depths of 400 meters with an average drill rate of about 1.5 meters per minute. One arrangement of the equipment weighs about 500 kilograms, and can be contained on two sleds, each about 3 meters long. Simplified performance equations are given, and experiments with nozzle design suggest a characteristic number describing the efficiency of each design, and a minimum bore-hole diameter very close to 6 centimeters for a hot water drill. Also discussed is field experience with cold weather, water supply, and contact with englacial cavities and the glacier bed.

Introduction

Drilling holes in glacier ice with high pressure hot water has become of increasing interest over the last several years for the following reasons:

- Growing scientific interest in basal sliding and sub-glacial water systems,
- A 20-fold increase in drill rate is possible over previous (electrothermal) techniques,
- The flushing action allows the drill to handle dirty ice easily; snow, firn, and ice can be handled with equal ease;
- The drill cannot overheat or burn out;
- The drill can be used for dye injection, and the jet is useful in rescuing stuck instruments.

Some disadvantages, compared to electrothermal drilling are:

- Difficulty of control;
- Equipment is more expensive, heavier, and maintenance is more specialized;
- A water supply is required, and operations are difficult at temperatures below freezing;
- Bore-holes are of larger diameter, and have irregular walls.

The most serious difficulty has been the lack of control due to the weight and bulk of the hose. This has been overcome in the system described here, which is the result of several years of design improvements and field experience.

Performance Equations

The following simplified mathematical relationships can be used to evaluate the performance of a hot-water drill:

Mass flow rate Drill rate Heat loss of hose Frictional head loss of hose

$$\dot{m} = K_1 \frac{(\bar{d})^2 R}{T_2} = K_2 \frac{(k/t)\pi d_m l}{\ln T_1/T_2} = K_3 \left[\frac{h_f}{L} d_i^5 \right]^{1/2} \quad (1)$$

where:		Metric units	English units
$\dot{m}$	mass flow rate	kg/hr	lb/hr
$\bar{d}$	average bore-hole diameter, nozzle contribution only	cm	in
R	drill rate	m/hr	ft/hr
k	coefficient of thermal conductivity of hose material	cal/hr-cm^2-°C-cm	B/hr-ft^2-°F-ft
t	hose wall thickness	cm	in
d_m	hose mean diameter	cm	in
l	hose length down the hole (depth of drill)	m	ft
T_1	hose inlet temperature difference above freezing	°C	°F
T_2	hose outlet temperature difference above freezing	°C	°F
h_f	frictional head loss in hose (equivalent water column height)	m	ft
L	Length of hose	m	ft
h_f/L	fractional head loss	m/m	ft/ft
d_i	hose inside diameter	cm	in
K_1	constant	5.78	44
K_2	constant	0.1	1.0
K_3	constant	663	1.5 X 10^4

$$\eta = \text{thermal efficiency of hose delivery} = \frac{\text{heat output at nozzle}}{\text{heat input top of hose}} = \frac{T_2}{T_1}$$

For the Synflex* 3000-06 hose, and nozzle (fig. 9) described later:

value of	metric units	English units
$(k/t)\pi\, d_m$ =	44.3	2.94
k =	3.72	0.25
$d_i^{\,5}$ =	0.786	7.42×10^{-3}
head loss across the nozzle		
5.5 bar (80 psi) =	56 m (of water)	185 ft

Also useful for converting h_f to units common on presssure gages:

1 psi = 0.433 ft of water

1 bar = 10.2 m of water

1 kPa = 0.102 m of water

The derivation of these equations, and the simplifying assumptions are as follows:
- mass flow rate is constant;
- ice is temperate; ice and ambient water at 0°C;
- all heat melts ice somewhere in the bore-hole;
- bore-holes are water filled, or nearly so;
- pump work can be ignored in calculating thermal efficiency of the hose. This is the heat generated by the frictional loss of head in the hose and only affects the efficiency calculation by about 1 percent.

Drill Rate:

From energy balance in melting ice at the nozzle:

$$\dot{m}\, T_2 = (\text{const})\, \frac{\pi (\bar{d})^2}{4}\, R$$

rearranging, $\dot{m} = K_1 \dfrac{(\bar{d})^2 R}{T_2}$, with K_1 determined by consistent units and standard values for the specific heat and the heat of fusion of ice.

Heat loss of hose

Assume also:
- constant overall heat transfer coefficient, U;
- constant specific heats;
- no phase changes of water in hose;
- no significant boundary layer effects. This is reasonable because the flow in the hose is turbulent (Reynold's number about 3×10^4), with a resultant surface heat transfer coefficient about 60 times that of the heat transfer coefficient of the hose material. The hose outside surface is assumed to be at the ice temperature. A thermal boundary layer here, if any, would increase performance.

$T_1 - T_2 = \Delta T$, the hose terminal temperature difference. Letting c be the specific heat of water, the heat loss (Mark's 1964), is then $\dot{m}c\Delta T$, which with these assumptions is also $UA(\Delta T)_m$, where A is the circumferential area of the hose, and $(\Delta T)_m$ is the logarithmic mean of the terminal temperature differences, and defined as:

$$\frac{T_1 - T_2}{\ln T_1/T_2}$$

since $U = k/t$, and $A = \pi d_m l$, equating the heat losses gives:

$$\dot{m} c \Delta T = \frac{(k/t)\pi d_m\, l\, \Delta T}{\ln T_1/T_2}$$

Dividing each side by ΔT, letting c be unity, and applying K_2 for consistent units gives the hose heat loss part of equation 1.

The thermal efficiency of hose delivery, η, can be defined as the ratio of heat output to heat input, which is:

$$\eta = \frac{\text{heat out the nozzle}}{\text{heat input to hose at surface}} = \frac{\dot{m}\, T_2}{\dot{m}\, T_1} = \frac{T_2}{T_1}$$

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* Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey

and since $\ln \frac{T_1}{T_2} = \frac{(k/t)\ \pi d_m\ l}{\dot{m}}$, η depends on the flow rate, the length and characteristics of the hose, and not on the choice of the inlet water temperature T_1. With a higher T_1, drilling is faster, but the same fraction of heat $(1 - \eta)$ is lost from the hose.

The coefficient of thermal conductivity, k, of the Synflex 3000-06 hose (described later), was determined during early field tests, and is tabulated as follows with handbook values of similar, or other possible hose materials:

material	k metric units	k English units
Nylon	4.5	0.3
Synflex 3000-06 hose	3.72	0.25
Polyethylene	3.0	0.2
Rubber	1.2	0.08
Polypropylene	1.04	0.07

Note also that $(k/t)\ \pi\ d_m$ is a constant for a particular hose, simplifying the use of equation 1.

Head Loss of Hose

Assuming steady, incompressible flow of water in pipes, the average cross-sectional water velocity, V, in the hose is:

$$V = \frac{\dot{m}}{\rho A},$$

where ρ is water density and A is the cross-sectional area.

The fractional head loss

$$\frac{h_f}{L} = f\ \frac{V^2}{d_i 2g}$$

(Streeter, 1958), where f is a friction factor governed by the surface roughness and the Reynolds number. The Reynolds number for the conditions of practical interest with this hose is about $2\text{-}5 \times 10^4$; which is the transition zone to complete turbulence. In smooth pipes this will vary f from about 0.021 to 0.027. In addition, there are the effects of fittings, connectors, valves, the hydraulic swivel on the winch, and the bends and deformations of the hose, each of which contribute to head loss. Instead of treating them individually, it is more convenient to lump them together and adjust f, which now becomes a "system" friction factor.

Field tests on this system showed this to be an equivalent increase in f to 0.035 which becomes part of the constant K_3.

Making the substitution of V, and rearranging, gives the frictional head loss part of equation 1:

$$\dot{m} = K_3 \left[\frac{h_f}{L}\ d_i^{5} \right]^{1/2}$$

with K_3 determined from the information given above. If this equation is applied to a system with a smooth hose only, and no restrictions (except for the nozzle), then K_3 should be increased by about 20 percent.

Note that h_f is expressed in the length unit of water head, and as h_f and L are expressed in the same units, the fractional head loss h_f/L has the same value in both metric and English units.

The head loss across the nozzle must be added to the head loss of the hose, h_f. For this final design (fig. 9) this loss was measured at 56 m of water (80 psi, or 185 ft of water), at a flow rate of 14.4 L/min. The total head loss is that required by the pump.

Note from these relationships the advantage of high pressure and a large, insulated hose to achieve high mass flow rates and high thermal efficiency. The practical limits are the bulk and weight of the hose, and the power available for the pump and heater. The necessary compromises have been made in the designs described here.

Laboratory Experiments

Laboratory experiments in clear ice about 50 cm thick were performed in March 1976 to determine the nozzle shape for efficient drilling. Testing started with the flat and round shapes and hole patterns (fig. 1), and progressed to larger and more pointed shapes (figs. 2 and 3) as the results developed. The maximum, free-fall drill rates were observed for mass flow rates of about 200 to 600 kg/hr and water temperatures of about 20 to 50°C. Temperature of the water flowing out of the top of the bore-hole and its diameter were also measured for nozzle B.

The clear ice allowed the observation of any impediment to progress, called a "cold spot", which could then be reduced or eliminated with a change in design. Also noted was the effect of a loss of water in the bore-hole, which turns a "wet" hole into a "dry" one such as would occur while drilling permeable ice, or upon intersecting a drainage crack.

The drill rates were proportional to flow rate and temperature (figs. 1-4), as expected from equation 1. The single hole in nozzle B (fig. 1), was found to be very important in forcing a turbulent stream of water ahead of the advancing nozzle. "Cold spots" were seen at the corner radii of the end of nozzle B, which suggested the more tapered nozzle E seen in figure 2. This design moved the "cold spot" back about 2-3 cm and gave no increase in performance. The next nozzle, F, seen in figure 3, with a longer taper and a larger diameter, was chosen as a result of the observation that the bore-hole diameter just behind nozzle B was about 2.3-3.2 cm over the test range. This made a somewhat more efficient drill, and moved the "cold spot" back to the tip again, which was, however, still too blunt.

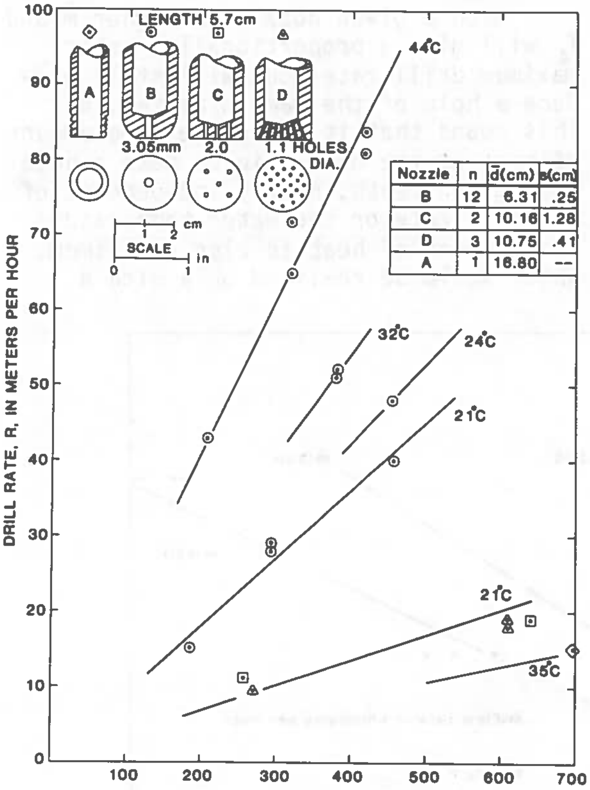

Figure 1. Block Ice Tests. Number of data points, n, with lines of slope $\bar{d}$ calculated from equation 1 at the nozzle water temperature indicated; s, the standard deviation of each set. Test nozzles made of brass. Drill rate proportional to flow rate.

The longer, tapered brass nozzles were seen to advance much more smoothly in a "dry" hole. Their shape, thermal mass, and conductivity were found to be important in removing the unpredictable number and pattern of "cold spots" that are encountered in a "dry" hole.

The final design is the brass nozzle G, shown in figure 9, which has a long, smooth parabolic taper to a pointed end, and is the one used in the drilling system. A small stainless steel tip was added later on the end of the nozzle to reduce damage from rocks.

As observed, a more efficient nozzle (for example, comparing B to C and D in figure 1) will advance at a faster rate for a given input $\dot{m}$ and T_z. This produces a bore-hole of smaller average

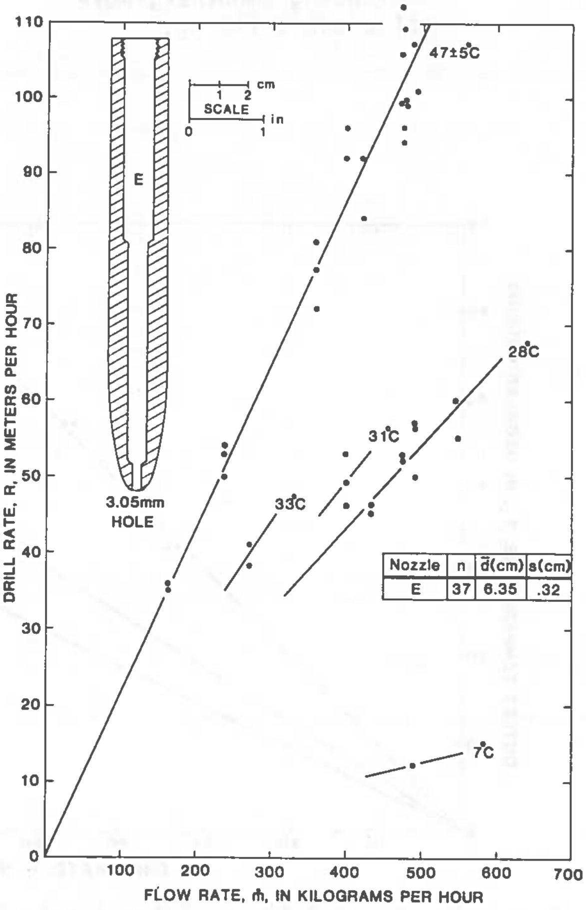

Figure 2. Test results for a longer nozzle E.

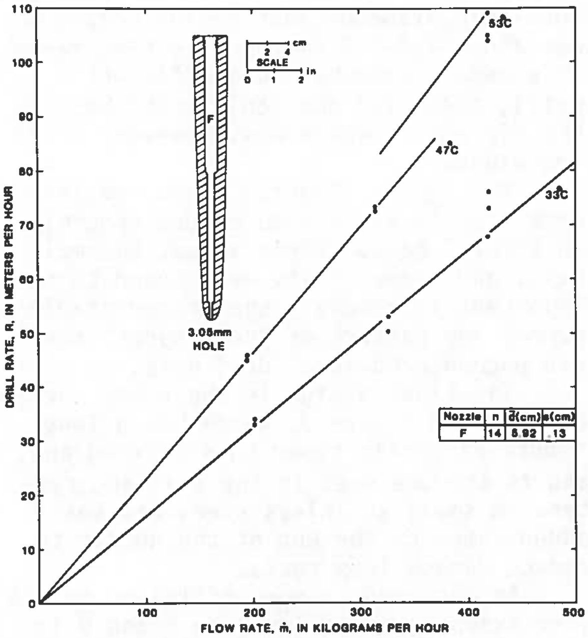

Figure 3. Test results for a larger and more pointed nozzle F. Both $\bar{d}$ and s have smaller values indicating smoother, more efficient drilling.

diameter according to equation 1. Because $\dot{m}$, T_2, and R were measured for each nozzle, the final average bore-hole diameter, $\bar{d}$, could be calculated. This number was found to be characteristic for each nozzle tested, and nearly independent of the flow rate or the temperature of the drilling water. Thus $\bar{d}$ can be thought of as a "nozzle number", easy to determine in a laboratory test, and which then can be used in evaluating drill performance in the field. A smaller number indicates a more efficient nozzle design, (comparing figs. 1, 2, and 3, for example), and a smaller standard deviation, s, indicates smoother, more consistent performance.

A $\bar{d}$ of about 6 cm for a "good" nozzle can be expected, and may be difficult to reduce further as there may be a turbulent mixing and heat transfer limitation at the nozzle tip. This value has the advantage that it allows a drill stem and nozzle design of practical ruggedness and weight.

With a given nozzle, a higher $\dot{m}$ and T_2 will give a proportionally faster maximum drill rate, but will still produce a hole of the same diameter, $\bar{d}$. This means that it takes the same amount of heat at the drill tip to make a hole of a given depth, nearly independent of the mass rate or the water temperature. This amount of heat is also a minimum, which would be realized only with a

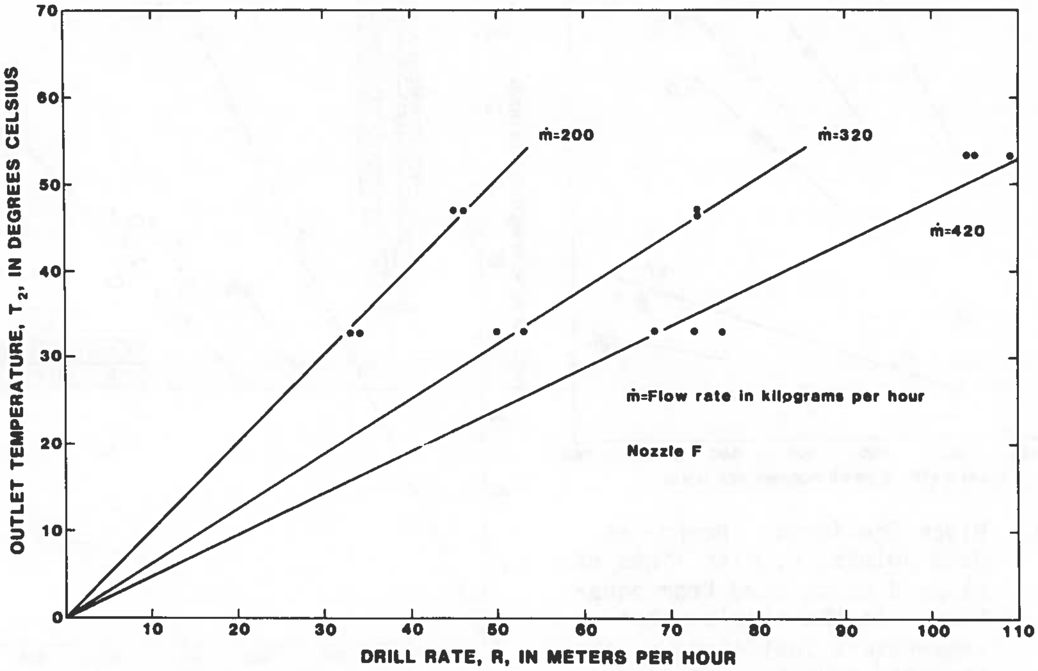

Figure 4. Data of figure 3 for nozzle F, with slope of lines $\bar{d}$ = 5.92 cm at the mass flow rates indicated. Drill rate proportional to outlet water temperature, T_2.

perfectly insulated hose when $T_2 = T_1$ for all l. What changes with a real hose is the fraction of the total heat input, 1 - η, lost through the walls of the hose, which only serves to increase the bore-hole diameter beyond $\overline{d}$. We can increase the efficiency, η, with a higher $\dot{m}$ or a better insulated hose, which reduces the total heat required for the hole to a value closer to the minimum, but will not change the minimum.

Some observations were made of the rate at which the hot water cools as it flows back up the bore-hole. The laboratory tests for nozzle B showed that about one-half of the bore-hole area defined by $\overline{d}$ occurs within 0.5 m above the nozzle. Field measurements while drilling in 1980 (described later) at 850 kg/hr and 63°C gave a 97 percent drop (to +2°C) within 15 m behind the drill in a hole estimated to be about 10 cm in diameter. Plus 1°C water was measured flowing out the top of the same bore-hole when the drill was at 152 meters, but this could easily be the effect of heat loss of the hose.

Field Experience

The first field tests during the summer of 1976 on South Cascade Glacier and Blue Glacier in Washington utilized a single rubber hose, 0.95 cm (3/8 in) inside diameter, a propane-fired water heater, and surface runoff water. We were able to achieve a drill rate of about 90 m/hr at a depth of 125 m using 8.5 L/min, 13.8 bar and 38C (2.3 gpm, 200 psi, 100°F). A drill stem 3.7 m long by 3.3 cm diameter (1 in NPS Sch 40 steel pipe) weighing 20 kg was used.

Many difficulties were encountered, mainly with the longitudinal stretch of the hose, estimated to be about 10 percent, which resulted in a jerky, uncontrolled advance of the drill. Realizing the critical importance of the hose characteristics to a successful design, a careful search was made of the commercial hose market, resulting in the selection of single, lightweight, flexible high-pressure hose of high longitudinal stiffness. This hose (Synflex 3000-06, described in figure 5) weighs 14 kg/100 m in air, and fortunately is nearly neutrally buoyant in water. Thus for a water-filled bore-hole the hose tension is nearly independent of depth. It has subsequently been used by several others (Kamb, W.B., Clarke, G.K.C., Hooke, R. LeB., oral commun.).

The mathematical relationships used in selecting and evaluating the parameters of hose size, radial heat loss, pump pressure, and mass flow rate were then applied to an improved design.

Drilling during the summer of 1977 on South Cascade Glacier using an oil-fired water heater and an electric pump at 11.4 L/min, 34 bar, 80°C (3 gpm, 500 psi, 175°F) achieved drill rates of 160 m/hr near the surface, decreasing to 125 m/hr at 50 m, and 60-70 m/hr at the 210 m depth of the glacier bed.

A technique for finding englacial cavities that was used with the earlier electrothermal drills is to support the drill with a constant tension device set at less than the drill weight. The drill advances at its maximum rate, and when a cavity is encountered the drop is noted by the operator. This technique was tried unsuccessfully with the hot-water drill. A strong longitudinal oscillation of about 2-3 Hz, called "bucking", would occur, which we attributed to the plugging and release of the nozzle jet against the ice at the bottom of the bore-hole.

The technique finally settled on was to lower the drill with a variable-speed winch at a rate slightly less than the free-fall maximum. If lowering rate is increased slightly the "bucking" oscillation is encountered, and the winch speed can then be reduced. Because the drum diameter decreases with depth, as does the drill rate, the actual required changes in winch speed are quite modest. The drill rate was about 3 m/min at the surface, 2 m/min at 75 m, and about 1 m/min at the 200 m depth of the glacier bed. The average was 84 m/hr.

An inclinometer was used in one of the holes and indicated a deviation of only a few degrees from the vertical; 4°4' maximum, returning to 1°35' from the vertical at 200 m. Fuel consumed was about 6.6 L/hr (1.7 gph). During this season 12 additonal holes were made to the glacier bed. These tests confirmed the important design features and helped to develop a basic drilling technique of controlling the lowering rate of the drill to achieve vertical holes. The longitudinal stiffness and the neutral buoyancy of the hose allows the operator to feel the probe weight during advance, to ensure that it is hanging freely, and to note contact with the bed.

For the 1979 summer season on South Cascade Glacier the development had progressed to a convenient sled-mounted unit using an oil-fired commercial water heater, and an electrically driven pump producing 14.4 L/min, 55 bar, at 77°C (3.8 gpm, 800 psi, 170°F). Fuel rate for the heater was about 9.8 L/hr (2.6 gph). Surface meltwater was used and expended down the hole. The drill system requires about 4 kW of electrical power which was obtained from the cabin generator system using a 1.5 km long power cable and 1 kV step-up and step-down transformers.

A drill of this design utilizing a 5-hp, gasoline engine-driven pump at 69 bar (1,000 psi) was used on the Variegated Glacier, Alaska, successfully drilling at least 12 holes to the bottom at 400 m (Kamb, oral commun.). The author was responsible for the construction of this equipment, shown in figure 6. Drill rate at 300 m was about 60 m/hr, and a total of about 5-1/2 hours of drill time was required to reach the bed.

The drill became stuck several times during retrieval, which was traced to the tendency of the warm hose to side-melt the hole producing "key-hole" shaped cross-section. The longer drilling time at Variegated Glacier had forced this difficulty to our attention. To remedy this problem removable spacers of 5.1 cm (2 in) diameter on the hose at 5 to 10 m intervals were introduced, and TV inspection of a bore-hole during September on the South Cascade Glacier showed no noticeable "key-hole" effect.

An improved spacer design, first used during summer 1980, is shown in figure 10. Spacing was 5 m, and installation and removal occurs just above the bore-hole utilizing a simple tool.

The advance rate of the drill was also held to about 1 m/min resulting in a larger diameter of at least 7.6 cm (3 in) as determined with a reamer of this diameter which freely passed both ways to the bed in two different holes. This was done to ensure an adequate diameter for the safe passage of a TV camera. The clearance also allowed the weighted drill stem to hang more freely near the center of the hole, and meter wheel readings were always within a few meters of the expected depth.

A snow melter was designed and tested successfully at South Cascade Glacier in anticipation of drilling in early spring, when no surface or reliable firn water supply could be expected. For example, while 77 L/min could be pumped from a firn well in September 1979, only 2.5 L/min was available in November (Krimmel, R.M., oral commun.). The snow melter, shown in block diagram in figure 5, consisted of a sled-mounted tub having a volume of about 2 m^3 with an overhead array of spray nozzles and recirculated hot water from a heater and pump separate from the drill system. Snow was shovelled into the tub, and the accumulated

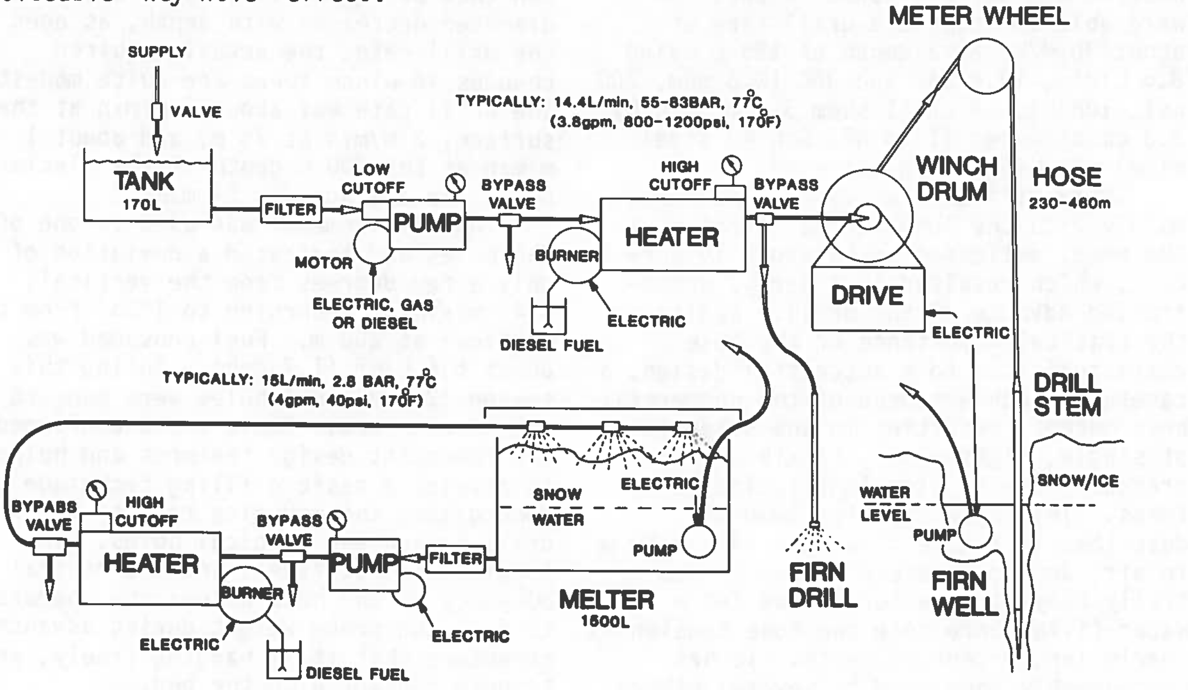

Figure 5. Block Diagram of the Drilling System. Additional equipment notes on the facing page.

EQUIPMENT NOTES FOR BLOCK DIAGRAM, figure 5

DRILL CIRCUIT, mounted on two sleds, figure 7, or as shown in figure 6:

Drill Supply Tank - 170 L (45 gal), polyethylene, tub with open top

Filter - Cuno 1M1 with G78L2 cartridge (50 micron)

Pump - Giant P-41, max rating 3.5 hp, 17 L/min, 83 bar (4.5 gpm, 1200 psi), with Eaton D41L-2416 automatic centrifugal clutch, pressure relief valve, bypass valve, pressure gage, vacuum-type low water cut-off, driven by 240-v, 2-hp electric motor, or 5-hp Briggs and Stratton gasoline engine, or 5-hp Petter diesel engine, aircooled. All motors require v-belt speed reduction to pump.

Burner and Heater - Alkota 300, diesel oil-fired, 75,600 K cal (300,000 BTU) per hour rating, 110-v, 5-amp, with temperature gage, high-temperature cutoff, and bypass valve.

Winch Drum - holds up to 460 m (1500 ft) of hose, with Chickshaw hydraulic swivel.

Winch Drive - 110-v, 3/4-hp, variable speed with two-speed gear change from 0.038 to 110 m/min.

Meter Wheel - 1-m circumference, contoured for hose, 1-cm readout.

Hose - Synflex 3000-06, Samuel Moore Co., Eaton Corp., Mantua, Ohio, 0.95 cm (3/8") I.D., 1.63 cm (0.642") O. D., rated working pressure 155 bar (2250 psi), weight in air 14 kg/100 m (9.4 lb/100 ft), polyurethane cover, synthetic fiber braid over a nylon core tube; swaged termination fittings can be replaced in the field (male end P/N 3903-06506, female end P/N 3903-06546). Maximum continuous length available is 76 m (250 ft).

Drill Stem - 3.3-cm diameter by 3.7-m long (1" NPS pipe), 20 kg, filled with lead shot around central tube. Nozzle of figure 9 can be replaced easily with 5.08-cm and 7.62-cm diameter (2- and 3-in) reaming nozzles (not shown).

Firn Pump - compact submersible type, 110-v, 2-amp, 15 L/min at 6-m head (4 gpm at 20-ft), used also in the Melter tub.

Firn Drill - hand held, 2.2-cm diameter by 2-m long (3/8 NPS pipe), with Spraco 15A4 spray nozzle, used to make firn well, or to recirculate water back to drill tank when used as a "mini" snow melter.

MELTER CIRCUIT, mounted on single sled (not shown), similar to sled shown in figure 7.

Melter Tank - 1500 L(390 gal) polyethylene tub with open top and removable cover, three each Spraco 15A4 spray nozzles, shovelled full of snow about every 20 minutes. If full of water at start, 200-m hole can be drilled without stopping.

Pump - Teel 3P569A, 1/2-hp, Rotary Screw type, with pressure gage and bypass valve. 110-v, 8-amps.

Burner and Heater - same as used with drill.

APPROXIMATE WEIGHTS: Melter circuit equipment sled; 700 kg (1500 lb). Drill Equipment Sleds: As shown in figure 6; 500 kg (1100 lbs). As shown in figure 7; 1200 kg (2500 lbs).

Weights do not include water, fuel, or generator.

water transferred to the drill circuit as required. The drill supply tank, also an open tub, was also used as a snow "mini-melter" utilizing a hand-held firn drill. This would accumulate enough meltwater for about 10 minutes of drilling.

By the summer of 1980 the equipment and the drill techniques had progressed to a point where operational reliability was achieved. About 3-1/2 to 4 hours were required to drill to the bed at 200 m and return to the surface. The equipment was mounted on sleds, shown in figure 7. At least 9 holes to the 180-200-m deep bed at South Cascade Glacier were made for basal water-pressure studies, and approximately 10 holes to 400-m depth at Variegated Glacier. TV inspection of the holes showed consistent, nearly circular cross sections.

The drilling at South Cascade Glacier during 1981 started in April with no reliable firn water supply, and experiments were conducted in an attempt to drill using recirculated water from the bore-hole. These efforts were unsuccessful in producing a reliable circuit due mainly to the complexity of having to handle hoses, cables, and pumps in a 14-m hole, and an unpredictable water level at 10 m. No reliable cross-connection could be made between adjacent holes. Kamb had somewhat better luck at Variegated Glacier in 1982, but reports that the supply was not completely reliable (oral commun.). The ability to recirculate water was found to be very dependent on the depth and permeability of the overlying firn and snow, and on the behavior of water found or placed there. The snow melter was then set up at the South Cascade Glacier, and about 14 holes were drilled to the bed in this manner. Melting snow is hard work, doubles the fuel consumption, and the extra equipment must be moved and maintained.

Drilling becomes difficult when the air temperature is less than about -5°C because of the risk of serious damage to the system from freezing water, especially in the high pressure pump, heater coils, and the hydraulic swivel on the winch drum. Compressed air was used on this spring trip to blow out the lines at night, but was not completely reliable in preventing ice plugs in the coils of hose on the drum. Flushing with anti-freeze, using about 20-40 L (5-10 gal) of 25-percent mixture gave protection to about -12°C. This was added to the drill supply tank when nearly empty, and the system shut down when the fluid first

Figure 6. The Cal Tech sleds on Variegated Glacier, Alaska. Portable generator at the right, 55-gal fuel drum for the heater in the foreground. Gasoline engine-driven pump is behind the drum, between the tank and the heater. Hose reel, drive unit on the left sled. Operator on the far left is tending a cable to a pressure transducer down the same hole.

appeared at the drill stem. As an added precaution, hoses were disconnected, and the pump run dry for a second or two. Upon startup the next morning about half of this mixture could be recaptured to be used again at the end of the day.

The real problem comes during an unforseen shut-down due to an electrical, fuel or water supply problem, as an ice plug can quickly form making it difficult or impossible to reestablish flow when the trouble is fixed. One must then work quickly to disconnect as much as possible and get anti-freeze at least through the pump and heater or they will be ruined.

Several of the holes drilled during the 1981 season had to be abandoned at mid-depth when the drill would suddenly stop its advance as if hitting a large rock, and would not continute despite 10 to 30 minutes of continued melting. This had happened at least three times in the previous years, and was also noted at Variegated Glacier (Kamb, W.B., oral commun.). This stoppage was finally discovered to be caused by the drill encountering an englacial water-filled cavity. The drill stem would pass through the edge of the cavity, but would not side-melt enough to pass the first hose spacer which was located 6 m up the hose. Once it was understood what was happening, it was a simple matter to back up the drill, melt out the restriction, and continue drilling.

Because the holes were to be used for TV studies at the bed it was important that the diameter of the bore-hole near the bed be of constant cross-section. A tensiometer was designed for the hose and was used to monitor the weight of the drill stem, and is shown in figure 10. This alerted the operator within 10-15 seconds of any drill hang-up, and was also used to determine contact with the bed. Hot water pumping could then be immediately terminated and the drill withdrawn, insuring the minimum hole di-

Figure 7. USGS Drill Sleds, South Cascade Glacier. Hose reel, winch drive, and boom sled in the foreground. Sled behind carries (right to left) the drill tank, electrically driven, high-pressure pump, water heater, and fuel tank. Operator is installing a hose spacer. Hose in the foreground brings water from a firn well near the previously drilled hole. Sleds are transported with a small track vehicle.

ameter at the bed to support the TV camera. Subsequent inspection with the camera would determine whether it was the bed, or debris above the bed that had been reached.

Walls of the bore-hole were scalloped, but quite regular in average diameter. A sliding, spring-loaded centralizing device which was used to hold the TV camera had no trouble making smooth passages along the bore-hole. Care had been taken while drilling to hold a steady rate of advance with the winch control, and to immediately stop the pump and heater during any interruption. This was especially important considering the cost and critical nature of the instruments which were to be lowered.

Figure 8. The hot-water drill stem.

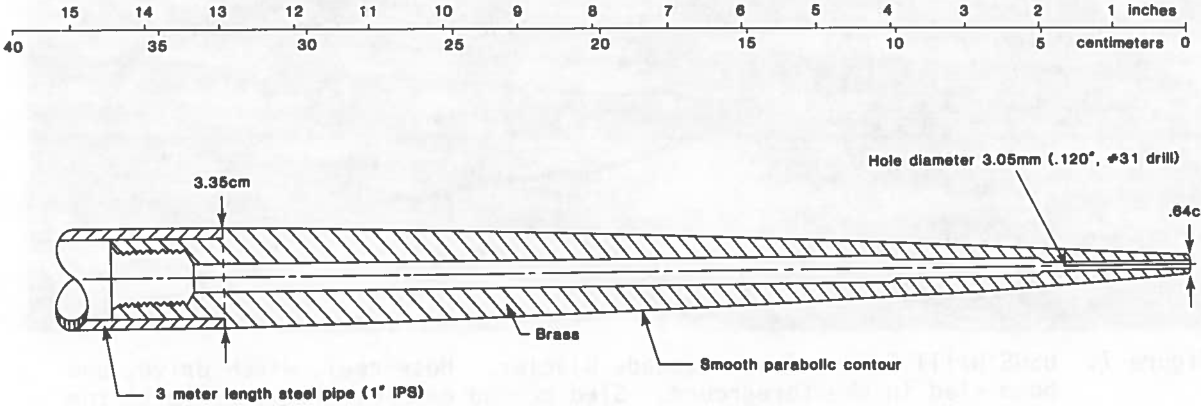

Figure 9. Drawing of the nozzle shown in figure 8.

A high-pressure pump driven by a 5-hp, air-cooled diesel engine producing 15 L/min at 55 bar (4 gpm at 800 psi) was successfully tested so that operations could be considered in the future at locations with only a 2- or 3-kW, 120-V portable generator.

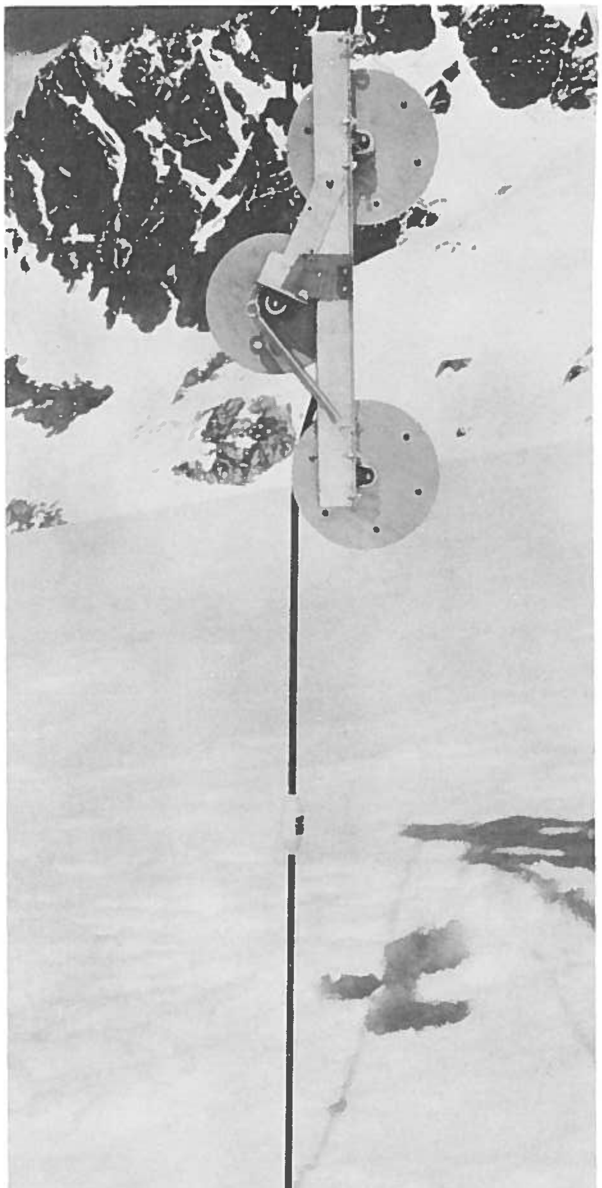

Figure 10. Hose Tensiometer, which can be easily installed and removed. A spacer has just been installed on the hose. Drill rate about 1 m/min.

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