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BAS HOT WATER DRILLING ON RONNE ICE SHELF, ANTARCTICA

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Abstract: The British Antarctic Survey (BAS) has developed a hot water drilling system that was successfully used during the Antarctic summers of 1990/91 and 91/92 to penetrate ice 562 m and 541 m deep on Ronne Ice Shelf, Antarctica. The hot water drill currently incorporates 300 kW of heating power with a water recirculation system, removing the need for continuous snow melting while drilling. In total, approximately four tonnes of aviation fuel were burned at each of the two sites, allowing a hole 0.2–0.25 m in diameter to be drilled over a period of 1 to 3 days, and maintaining it, through repeated reaming, for a further five days. Ice temperatures of −26°C caused rapid refreezing of the hole and successive borehole caliper profiles indicated initial closure rates of 11 mm hr-1, decreasing to 5 mm hr-1 after the hole had been open for a number of days. Access to the sub-ice shelf oceanographic environment allowed measurements to be made in the underlying seawater and the installation of thermistors in the ice and the ocean for long term temperature monitoring. In forthcoming field work, the drill will be used to penetrate ice approximately 850 m thick to gain access to the underlying seawater and deploy a string of oceanographic instruments with a diameter of 0.14 m, necessitating further improvements in the drill's reliability and performance.

1. Introduction

The BAS hot water drill was developed to obtain direct oceanographic observations from beneath George VI Ice Shelf and later Ronne Ice Shelf. The original Hot Water Drill (HWD) was modelled on systems successfully operated in Switzerland (IKEN *et al.*, 1977) and Arctic Canada (NAPOLÉONI and CLARKE, 1978) and provided a means of rapidly gaining access to the sea water beneath George VI Ice Shelf for a period of hours or days (COOPER *et al.*, 1988). Over recent years work on Ronne Ice Shelf has placed more demands on the HWD, ideas were adapted from other drilling projects such as the Ross Ice Shelf Project at J-9, Antarctica (KOCI, 1984), Jakobshavns Glacier, Greenland (IKEN *et al.*, 1989), Ice Stream B, Antarctica (HUMPHREY and ECHELMEYER, 1990). These ideas were successfully incorporated into the BAS hot water drilling system and a programme of hot water drilling on Ronne Ice Shelf began in the 1990/91 austral summer at S90/1, a site 300 km from the ice front (see Fig. 1). The drilled holes are used to provide direct and accurate measurements of the ice thickness, confirming depths obtained using seismic and radar techniques. The access to the underlying seawater allows conductivity-temperature-depth (CTD) profiles of the water column to be obtained together with water samples which can be analysed for oceanographic tracers such as δ18O and δD. The salinity, temperature and tracers collectively provide a "signature" of the water masses which can be used to identify the origins of the water and their subsequent interactions with the ice shelf. Once oceanographic profiling has been completed it is possible to deploy a range of instrumentation to monitor temperature, conductivity and current speed and direction. The instruments are clamped to a cable, and are regularly logged providing long time series of measurements from within the ice shelf, the water column and across the ice/ocean interface. Such data sets are capable of revealing changes in ice shelf temperatures (Paren and Cooper, 1988), basal melt rates (Grosfeld *et al.*, 1992) and fluctuations in the characteristics of the water column (Nicholls *et al.*, 1991). Knowledge of these directly observed parameters beneath ice shelves aids mass balance studies and the understanding of the dynamics of ice shelf and ocean, and the ice/ocean interaction.

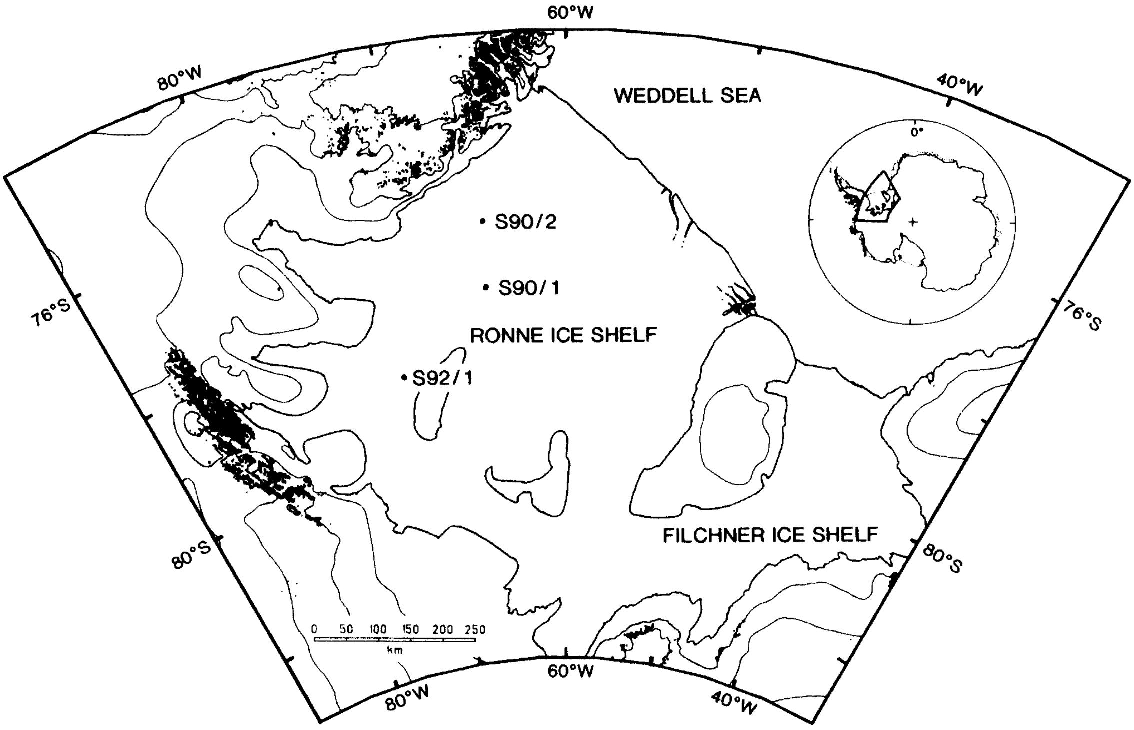

Fig. 1. Map of Ronne Ice Shelf indicating locations of hot water drilling sites, S90/1, S90/2 and S92/1.

2. Criteria for HWD Design

For oceanographic work to be undertaken beneath an ice shelf, a hot water drill must be capable of drilling a hole of sufficient diameter to the base of the ice shelf, and maintain it for a number of days. Knowledge of ice thickness, ice temperature profile, borehole refreezing, and the drills thermal characteristics will allow the depth capabilities of the drill to be assessed. Estimates of drilling and reaming times can be obtained. With present BAS logistical resources, fieldwork on Ronne Ice Shelf is primarily supported by Twin Otter aircraft based at Rothera, some 1200 km to the north. Minimising the total cargo of equipment and fuel is given high priority. The drilling equipment is frequently manhandled during transportation to the drilling site and the drill is designed to maximise the manageability of individual items. The drilling team consists of four personnel and it is essential that each element of equipment can be moved by that many people, limiting the weight of individual items and requiring that they be fitted with skids for easy transport around the drill site. The bulk of some items is also limited by the size of the cargo hatch in a Twin Otter, these have to reassembled in the field.

Reliability is an important factor when considering the remoteness of field locations. An adequate supply of spares or better, replacement equipment, are ways in which reliability can be improved, though this adds to the financial and logistical costs. To minimise the cost of drilling components, commercially available equipment is used, modified for field use, and integrated into the existing drilling system.

A critical decision that had to be made concerned the diameter of the hole to be drilled in order to carry out the oceanographic work and final deployment of instrumentation. A larger diameter hole would allow the use of a wider range of standard oceanographic equipment, or equipment that needed only minor modifications. However, the cost in logistics to get the larger fuel load to the drill site would have been unacceptable. Instead, the minimum diameter of the CTD equipment used for repeated profiling of the ocean was defined as 0.06 m, though instruments for permanent deployment only pass down the hole once and can be of significantly larger diameter.

3. Meeting the Design Criteria–Choice of Equipment

The BAS hot water drill is under continual development to meet the increasing demands placed upon it, the need to integrate new equipment into the existing system is essential. Currently, the drilling system is being prepared to operate to a depth of 850 m with a view to further increasing the depth capability in the near future, enabling access to be gained to the sea beneath most of Ronne Ice Shelf. To obtain satisfactory drilling rates at increased depths, flow rates have to be increased while maintaining the temperature of the water at the surface. The penalty incurred by increasing the flow rate is an increase in the required water pressure. Currently the drilling system uses 13 mm (1/2") bore hose, rated to 140 bar, a limit that has now been reached due to the increased hose length, dictating that water flow is reduced slightly. To increase or at least maintain drilling performance at greater depth, water temperature at the nozzle can be increased by increasing the surface outlet temperatures. Hose was obtained that had a safe operating temperature of 125°C (rather than 93°C).

To keep the fuel requirements to a minimum, a water re-circulation system was used, any thought of melting snow continuously was unrealistic and would double the fuel requirements. A system similar to that described by KOCI (1984) was used and consisted of two parallel holes interconnected at a depth below sea level (see Fig. 2 and Table 1). The interconnection consisted of a cavity in which the submersible pump was suspended. Maintaining the pump at a depth below sea-level (or the ultimate water level once a hydraulic connection with the sea had been achieved) meant that water could be retrieved throughout the entire operation. As the submersible pump was to operate continuously for long periods, there was a strong possibility of it becoming frozen into the hole, a problem encountered several times in the past. This was countered by fitting a spray to the submersible pump, allowing hot water to be introduced into the cavity and over the pump. An additional advantage of this arrangement was that the temperature of the water pumped to the surface was maintained at a few degrees above freezing. This, together with the use of anti-icing paste (a form of grease) on the hoses and cables, reduced their chances of

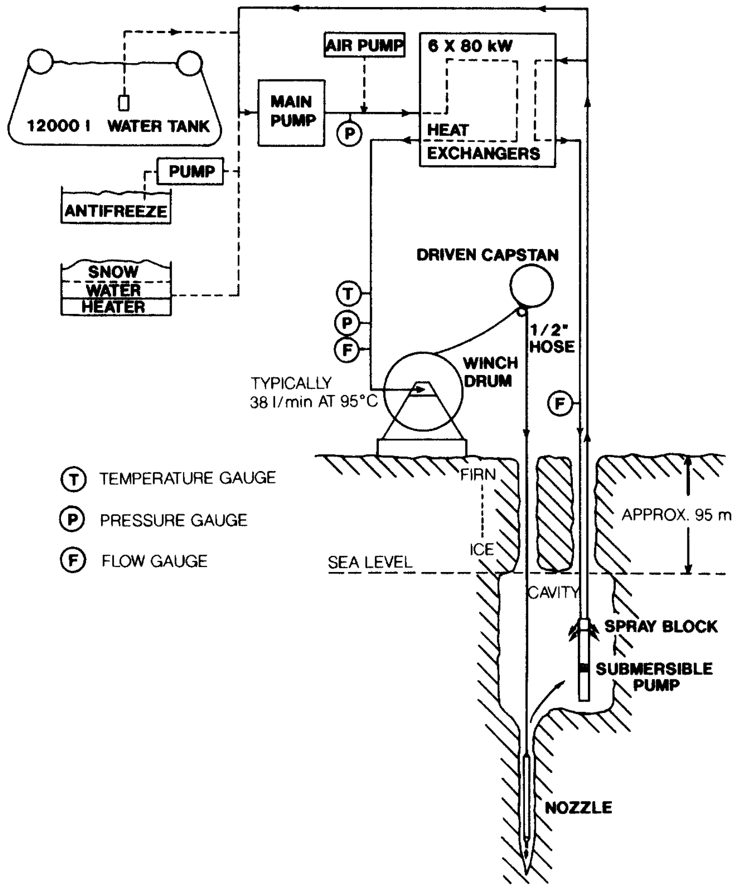

Fig. 2. Block diagram of the drilling system to be used on Ronne Ice Shelf to drill through ice 850 m thick at S92/1 (see Table 1 for details).

freezing to the side walls.

The generator and main water pump were both powered by identical diesel engines, thereby reducing the number of spares needed. The increased weight of the diesel engines compared with petrol alternatives was easily offset by their reliability and ability to run them on Avtur, a fuel readily available at existing field fuel depots.

The drilling nozzles were designed to combat the problems of depth and cold. The 30 mm nozzle head had the same smooth parabolic profile as designed by TAYLOR (1984). On the larger nozzles (see Fig. 3) the front cone spray washes over the drill itself rather than pointing forwards. This design has been used very successfully, giving good penetration rates, uniform holes, and is ideal for drilling and enlarging holes in firn. A conical spray at the back of the nozzle was considered necessary in case the nozzle became trapped by rapid refreezing above it, a problem described by HUMPHREY and ECHELMEYER (1990) when drilling is carried out close to the depth limit of the drilling system. It has a less powerful drilling action than the front cone spray but would still prove effective against hole closure, allowing recovery of the nozzle. The back cone spray operates continuously. The forward spray is used primarily with the 52 mm nozzle and operates over an angle of 30° ahead of the nozzle before the front cone spray takes over in enlarging the hole.

Table 1. Equipment notes. (see Fig. 2)

Water storage tank – 12 m^3 capacity weighing 50 kg when empty, made from polychloropene coated fabric.

Submersible borehole pump – Compact multistage centrifugal pump, 1.5 m long and 90 mm diameter. Capacity of 60 l min^{-1} from 80 m and is electrically powered (240 V, 13.5 A).

Burners and heat exchangers – Six units each with burners rated at 80 kW when burning avtur. Electrical power consumption: 150 W. Temperature gauge with an adjustable high-temperature and low-flow cut-out. The heat exchangers consist of two concentric coils made from seamless tube rated to 140 bar (2000 psi).

High pressure pump (main pump) – A stainless steel Triplex plunger pump, rated at 38 l min^{-1} at 1000 rpm, with a maximum pressure of 150 bar (2200 psi). The pump is self-priming, with pressure relief valve and pressure gauge, and is powered by a diesel engine (see below) *via* a 'V'-belt speed reduction.

Generator (not shown in Fig. 1) – A 5 kVA, 4 kW alternator rated at 240 V, 21 A, 50 Hz at 3000 rpm is powered by a diesel engine (see below).

Diesel engines – Lister Petter AD2 air cooled engine with maximum power output of 11 kW (15 HP). Fuel consumption is 0.45 l kW^{-1} hr^{-1} at 3000 rpm. It is hand-started and is fitted with a pilot ether start to assist if difficulties are encountered at low ambient temperatures.

High pressure hoses – Dunlop thermoplastic hose with a fabric braid and 13 mm (1/2") bore, rated to 140 bar (2000 psi), operating range –40°C to 93°C with occasional use to 125°C. The hose couplings are swaged. Tensile tests have shown the hose will stand over 9000 N before failure, at which time the hose had elongated by 60%. The hose weight in air is 21 kg/100 m.

– Dunlop high temperature hose with a single wire braid and 13 mm (1/2") bore; rated to 140 bar (2000 psi); operating temperature range –40°C to 125°C, and weighs 45 kg/100 m in air.

Air pumps – Two units, electrically powered, each producing 100 l min^{-1} at 10 bar (150 psi).

Anti-freeze pump – Electrically powered 0.75 kW unit.

Drilling Winch – The winch has a drum capable of holding over 1000 m of 13 mm (1/2") bore hose and has a capstan wheel to raise and lower the hose. The drum and capstan are hydraulically powered.

Borehole three arm caliper (not shown in Fig. 2) – BPB Instruments CO1 caliper sonde, 1.90 m long, 38 mm diameter, rated to 2000 m and weighing 13 kg. It has a measurement range of 50 – 480 mm. The output is displayed graphically on a PC.

Monitoring equipment

Pressure gauges – Heavy duty glycerine-filled gauges, hermetically sealed. Pressure range of 0–140 bar (0–2000 psi) with accuracy of ±1.6% FSD.

Flow indicators – A sharp-edged orifice and tapered metering piston magnetically coupled to a rotary pointer is used to indicate a flow range of 3–70 l min^{-1}. It has an accuracy of ±4% FSD and a high or low flow alarm.

Temperature – Indicated at the drilling winch, and also at the heat exchangers which are switched off automatically at a presettable maximum (or minimum) temperature. Temperature range: 0 to 120°C.

Water depth – A pressure sensor measures the head of water above the submersible pump. The sensor is rated to 50 m water depth. It is linked by 100 m of cable to a LED display, accurate to ±50 mm and has a high and low level alarm.

Depth – The approximate depth and speed of the nozzle is given on a LED display that is linked to a rotary pulse generator located on the capstan wheel axel.

Subsequent reaming of an existing hole can present additional complications, such as those experienced by Engelhardt and Determann (1987) and described by Bässler and Miller (1989). They found that it was not possible to ream the hole because of difficulties caused by the deviation of the nozzle from the pre-drilled hole. To avoid completely the possibility of the nozzle cutting into the wall and forming a secondary hole, the hole is reamed using the 127 mm nozzle with the forward spray replaced by a "nose" section, 0.25 m in length. This is used to guide the nozzle down the existing pre-drilled hole.

4. Control of Drill Speed and Hole Size

In order to drill a vertical hole with a uniform diameter, the drilling speed must be

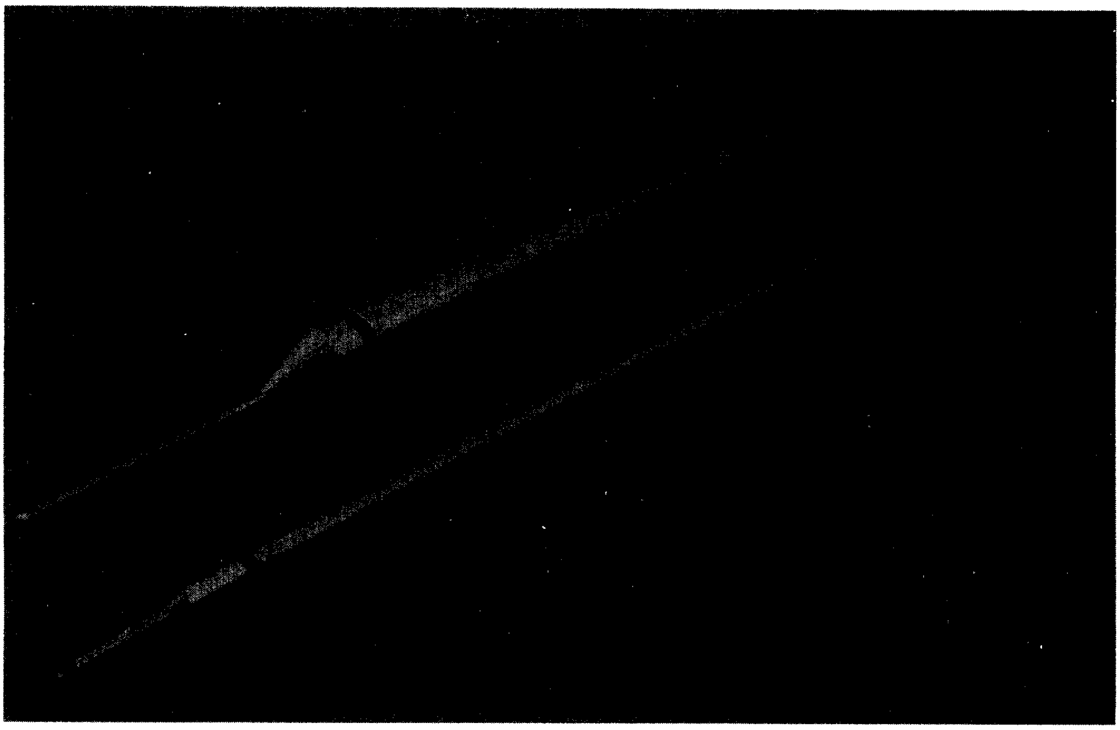

Fig. 3. Photograph showing the 52 and 127 mm drilling nozzles and spray directions.

reduced with increasing depth, this is determined by knowledge of the nozzle water temperature and rate at which it is lowered. In addition, surface water temperature and flow must also be carefully monitored and controlled.

For work on Ronne Ice Shelf, a drilling winch was used that consisted of a large dismantlable take-up drum capable of holding over 1000 m of 13 mm (1/2") hose and a driven capstan similar to that used by IKEN *et al.* (1989) on Jakobshavns Glacier, Greenland (see Fig. 4). This winch was hydraulically powered giving good control over drilling speeds. The instrumentation associated with the winch monitors drilling speed, nozzle depth, water temperature, pressure, flow and water level in the cavity. Alarms are fitted to several of these parameters to indicate to the driller if a breakdown occurs in the system.

As inclination of the hole is a parameter that is not measured, it is essential that the hose is never lowered faster than the nozzle can drill which would otherwise result in the nozzle resting on the ice at the base of the hole. Clearly, if the nozzle is no longer suspended it can start drilling out of the vertical. A non-vertical exit hole especially at the ice shelf base can cause the loss of oceanographic equipment: the suspension wire cuts into the side of the hole and makes a key-hole at the ice shelf base. It is then unlikely that the equipment could be raised back into the borehole. At depths greater than approximately 250 m it is not possible to detect by hand if the larger nozzles are freely suspended. To overcome this problem the front section of the nozzles incorporates a compressible mechanical valve system. When the nozzle is resting on the ice at the base of the hole, the weight of the nozzle causes the partial closure of a valve, increasing the back pressure. The increase is detected at the surface where the water pressure is being monitored, and the operator then reduces the speed of the winch. Additionally a load cell can be used to perform a similar function by measuring the reduced load on the hose when the nozzle

Fig. 4. The BAS hot water drill on Ronne Ice Shelf. In the foreground, the driven capstan using 13 mm (1/2") drilling hose and to its right the 25 mm (1") hose from the submersible pump 80 m below with the winch drum, hydraulic controls and four heat exchangers behind.

rests on the bottom of the hole.

In order to create a hole with a uniform diameter it is necessary to know the nozzle water temperature which decays exponentially as depth increases, provided that the water temperature and flow remain constant at the surface. No such direct measure is presently available, but calculations similar to those carried out by HUMPHREY and ECHELMEYER (1990) were used to estimate water temperatures at depth. These values together with previous experiences, provide an indicator for drilling speeds which can be varied according to the depth of the nozzle and the diameter of the hole required. A borehole caliper was then used to later confirm the hole diameter.

5. Current Method of Operation

Work carried out during recent field work on Ronne Ice Shelf has lead to a drilling strategy that best utilises the fuel available and satisfies the needs of the oceanographic work. Firstly, water from the storage tank is used to drill two parallel holes, approximately one meter apart, 0.25 m in diameter, to a depth that is below sea level. To establish the water recirculation system an interconnecting cavity is formed and drilling of the main hole can begin using the smaller nozzle. When the base of the ice shelf is first reached a pressure sensor in the cavity will indicate a sudden change in water level when the hydraulic connection is made with the ocean. The hole is then reamed to a diameter of up to 0.25 m using the 127 mm nozzle, the diameter is checked using a borehole caliper before any oceanographic work begins. To combat the constant refreezing, periodic reaming of the hole is essential to maintain the hole. The work then settles into a cycle of oceanographic and reaming work periods, this continues until fuel supplies dictate that the CTD profiling work must stop and a range of instrumentation is deployed to monitor temperature, conductivity and current speed and direction.

6. Field Performance

The drilling system described here was successfully used during the Antarctic summers of 1990/91 and 91/92 to penetrate ice 562 m and 541 m deep on Ronne Ice Shelf. The bulk of the ice column was later measured to be at about −26°C using thermistors frozen into the ice shelf. Over periods of seven to ten days approximately four tonnes of Avtur were burned at each site to form a hole 0.2–0.25 m in diameter and maintain it for almost 5 days, enabling oceanographic work to be undertaken. The drilling operations followed the method outlined above with two people drilling in twelve hour shifts. Once operating smoothly, the drilling normally required regular checks every 15 min with only minor adjustments to water temperatures, drilling speeds and occasional changing of fuel drums. Typically, only one person was necessary to maintain the system but many problems required additional help. To assist in the recovery of the submersible pump and its umbilical, two snow mobiles were available to haul it from the hole. The overall performance of the drilling system was satisfactory once details of the drilling strategy were worked out and operators became familiarized with the equipment.

The drilling site for the 1990/91 field season was located at 77°36'S, 65°42'W (S90/1). At the base of the ice shelf there was a 15 m unconsolidated slush region which could easily be drilled but which quickly “refilled” with slush after the drill was withdrawn. The slush layer could not be penetrated easily by the oceanographic instruments; this was only achieved by suspending a heavy streamlined weight 15 m below the instrument. At the slush layer the weight was repeatedly dropped several meters until it forced its way through to the sea, the instrument was then drawn down by the weight below. Over the two week operating period exhaust heat from equipment caused it to sink into the snow. The use of several wind breaks was found to be very useful during the drilling operations as work cannot stop for poor weather conditions.

For the following 1991/92 field season the drill site was located at 76°42'S, 64°55'W (S90/2), 100 km north of the previous drilling site and no slush layer was present at the ice shelf base. Many of the previous seasons problems were resolved. The reorientation of exhausts and extensive use of insulating materials prevented equipment and hoses sinking into the snow. The improved drilling system created a 0.25 m access hole in two days. However, because of problems with the submersible pump, the main hole had to be abandoned and a second hole drilled. During the drilling of the second hole the HWD was more reliable allowing better assessment of its capabilities and efficiencies. The access hole was drilled in a period of 24 hours. To drill a 541 m hole to the base of the ice shelf with an approximate diameter of 0.23 m it was necessary to vary speeds between 1.4 m min^{-1} near the surface and 0.7 m min^{-1} at the ice shelf base, while drilling and then reaming. A total of 640 kg of Avtur was burned (27.5 GJ) to heat 55 tonnes of water by 78°C (18 GJ), giving a combustion/heat transfer efficiency of 65%. Of the available energy contained in the water, 40% (7.2 GJ) was used to warm and melt the ice to form the hole, the remaining 60% (10.8 GJ) would maintain or, depending on the hole diameter, enlarge the hole, and warm the surrounding ice throughout the length of the hole.

7. Borehole Closure Rates

No comprehensive study of borehole closure rates by refreezing was carried out during the 1990/91 field work, although successive caliper profiles taken shortly after the hole had been drilled (2-3 hours after the hole had been created) showed initial closure rates of 9 to 11 mm hr^{-1}, for a hole diameter of about 0.13 m in ice at −26°C. Another pair of profiles were taken 13 hours apart with only oceanographic work, and no drilling, taking place during that period. The hole closure rate averaged over the 13 hours is shown in Fig. 5. Also indicated is the undisturbed temperature profile, obtained the following year from thermistors frozen into the ice shelf. The maximum closure rate calculated over that period was about 5 mm hr^{-1}, a figure that was confirmed during the 1991/92 field season by successive caliper profiles taken over periods ranging from 5 to 20 hours. It is likely that refreezing rates near the beginning of these periods were higher, dropping off as the

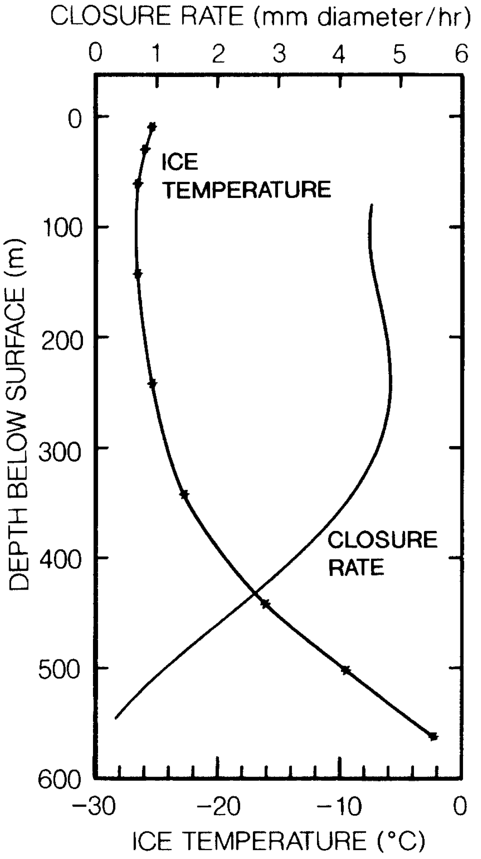

Fig. 5. Graphs showing the observed hole closure rate and undisturbed ice temperature profile at 77°36'S, 65°42'W (S90/1). The time period between the caliper profiles used in the observation of closure rate was 13 hours, and the hole diameter ranged between 140 and 200 mm.

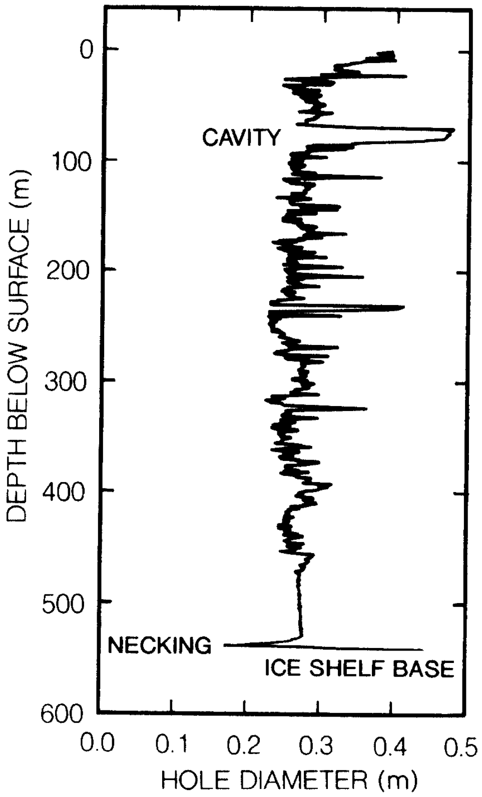

Fig. 6. A typical profile of borehole diameter obtained soon after reaming of the hole had finished.

insulating layer of warm ice built up on the walls of the hole.

The caliper profiles from 1990/91 showed that the borehole had an irregular diameter profile, with narrowings reducing the average hole diameter by 0.05 to 0.1 m. Since the relevant "diameter" of a borehole is its smallest diameter, narrowings cause a disproportionate wastage of fuel and time. Reaming the hole to remove the narrowings is a very inefficient procedure. With the construction of the new drilling winch, additional instrumentation and alarm system, narrowings of the hole no longer pose a significant problem, removing the need for small scale reaming, an example of such a caliper profile from the 1991/92 field season is shown in Fig. 6.

One exception where the diameter of the hole is always reduced despite careful drilling also is illustrated in Fig. 6. The smallest diameter of the hole is found at the ice shelf base, the feature known as "necking", is a characteristic of hot water drilled holes in ice shelves where the base is melting. The necking forms at the ice shelf base during drilling, a proportion of the hot water from the nozzle, rather than melting the surrounding ice and enlarging the hole, is dissipated into the sea water below, reducing the hole diameter. It is only with repeated reaming in this region that the necking can be reduced and is a significant feature that the driller should be aware of prior to the deployment of oceanographic equipment.

8. Conclusions and Future Developments

To date, BAS hot water drilling carried out on Ronne Ice Shelf has successfully been used to provide and maintain access holes to the sub-ice shelf oceanographic environment for periods of several days until fuel supplies have become exhausted. Throughout the whole operation constant refreezing of the hole is a major problem, placing pressure upon operators and testing the reliability of equipment, careful planning is required if hot water drilling is to be successful. Parameters such as ice temperature profile, refreezing rates, hole diameter and the heat loss characteristics of the drilling hose have to be taken into consideration to determine fuel requirements, logistical support for the project and the time period available for oceanographic work.

Throughout the drilling operation, careful monitoring of the drilling system is essential. Water temperature, flow rate, and speed of drilling are the primary parameters that must be regulated to ensure a hole with a uniform diameter. Simple alarm systems can be used to alert the driller when these preset parameter values are exceeded, ensuring immediate action is taken to rectify the situation, therefore maintaining the uniformity of hole diameter. For sub-ice shelf oceanographic work it is necessary to maintain the hole, through repeated reaming, to gain the greatest scientific benefits before the final deployment of any permanent moorings.

The need to further confirm the oceanographic processes beneath Ronne Ice Shelf will continue for some time to come. In forthcoming field work the drill will be used to penetrate ice approximately 850 m thick, located at 78°45'S, 71°45'W (S92/1, see Fig. 1) during the 1993/94 austral summer. Areas of the ice shelf, south of Berkner Island, Henry and Korff ice rises, have typical ice thicknesses of 1000–1400 m. To implement a successful drilling program in these locations, the hot water drill will require further modifications and additions. To achieve these goals, it is planned to increase the hose diameter from 13 mm (1/2") to 19 mm (3/4") and modify the drilling winch to accommodate the increase in hose diameter. This increase in hose diameter will allow flow rates to be doubled and water temperatures maintained by the addition of new pumps and heat exchangers. Data collected from a nozzle water temperature logger will assist in accurately determining the thermal characteristics of the hose, this coupled to models of freezing rates will further help to ascertain the optimum drilling strategy.

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