# THERMAL ICE DRILLING:

# AUSTRALIAN DEVELOPMENTS AND EXPERIENCE

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*ABSTRACT*

*During the past seven years the Antarctic Division has gained considerable experience in the thermal core drilling of intermediate depth boreholes. Following CRREL developments, a drill plant especially suited to the requirements of the Australian expeditions has been developed. The new drill is described; it features caravan housing, improved operator convenience and protective devices. Drilling experience and borehole logging instruments are also discussed.*

## Introduction

Ice drilling has become an important facet of glaciology, particularly for the study of historical changes in the polar ice sheets. Factors such as age, temperature of deposition, particle trajectories, impurities and crystalline properties require the application of ice drilling procedures for investigation. Techniques for the rapid core drilling of intermediate depth boreholes (to 500 m) by thermal methods have been developed over the past decade (Hansen and Langway, 1966; Ueda and Garfield, 1969). The impetus for thermal drill development was mainly the high cost, weight and logistics problems associated with rotary drilling plants (Langway, 1967, pp. 102-104).

During four seasons of field operations over the past seven years the Antarctic Division has core drilled eight intermediate depth boreholes using a thermal drill; more than 1600 m of core has been recovered. Experience with the thermal drilling technique was initiated in 1968 following the acquisition of a drill from U.S. Army CRREL. This drill successfully cored a 310-m hole in the Amery Ice Shelf during that year. The very adverse operational conditions experienced on the Amery Ice Shelf severely stressed both the drill plant and its operators. Under such field conditions, exposure, remoteness from base facilities, minimum staff and limited power made the operation extremely difficult. As future Australian operations in similar situations were intended a modified drill was designed. The new drill features caravan housing and other improvements for operator convenience, including automatic control during drilling, also protective devices, and electronic control of winch speed and drill-head temperature.

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The drill is convenient to operate and reliable in performance. However, several notable failures have occurred including loss of a drill head and cable.

**Principles of the Thermal Drill**

A practical thermal drilling system comprises a drill head, a means of raising and lowering this head and a cable to transmit power to it. The drill described here melts a hole of 1 cm diameter and takes a core of 11.75 cm diameter and 2 m long. The meltwater is drawn from the drill face by a vacuum pump and is stored in a tank on the drill head (Fig. 1).

Performance of a thermal ice drill is determined by the parameters of the thin layer of meltwater between the heated drill section and the ice. Drill efficiency and speed of penetration are dependent upon the mechanical configuration of the heated annulus, input power and drilling pressure, and the pertinent physical properties of the ice to be drilled, namely temperature and density (Shreve, 1962). Drill penetration rate is typically 4 cm per minute for a heater dissipation of 3.9 kW and an ice temperature of -20°C. Pendulum steering is essential for a plumb hole; this requires a controlled drilling pressure.

With increasing depth of the borehole, a greater proportion of the cycle time is lost in winching the head to and fro between the iceface and the surface. In general, this consideration and borehole closure caused by ice creep limits the practical depth for the present thermal drill in a dry hole to about 500 m.

The 385-m hole drilled at the summit of the Law Dome in 1969 took 21 days to complete on the basis of a two-shift 24-hour day, that is a total of 500 working hours, including maintenance periods. Drilling rates to 44 m per day have been reported by a group drilling at Casey in 1974.

**The Antarctic Division Thermal Drill**

The basic design objective was to produce a drill for use inland from established Antarctic stations that was self contained, easy to transport and convenient to operate; reliability was paramount for, in general, field operations under our conditions must be self supporting. The general mechanical arrangements of the thermal drill detailed in CRREL drawings series TS66-26 (drill head), TS65-13 (winch assembly) and TS66-34 (winch and tower) were retained. The Australian modifications largely have been described already (Bird and Ballantyne, 1971) but are presented here with the details of latest developments.

**General Construction**

Environmental protection against the Antarctic weather conditions (low temperatures, high wind and snow drift) is important for both the drill rig and operators.

The drill plant is installed within a caravan 3.7 m by 2.15 m and 2.15 m high; sledge mounting makes for maneuverability. The tower is sealed through the caravan roof and braced to its structure; flexible ducting allows the head to be elevated above the caravan roof for removal of the ice cores. A flexible tube connects the caravan floor to the borehole entrance tube and ex-

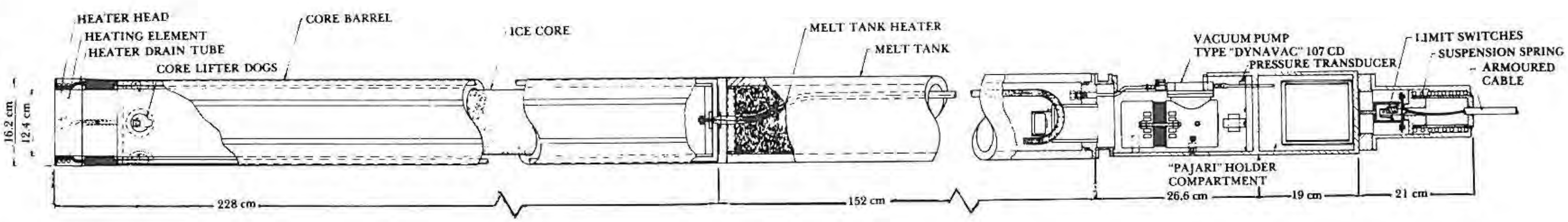


Figure 1. Schematic diagram of the thermal drill (not to scale).

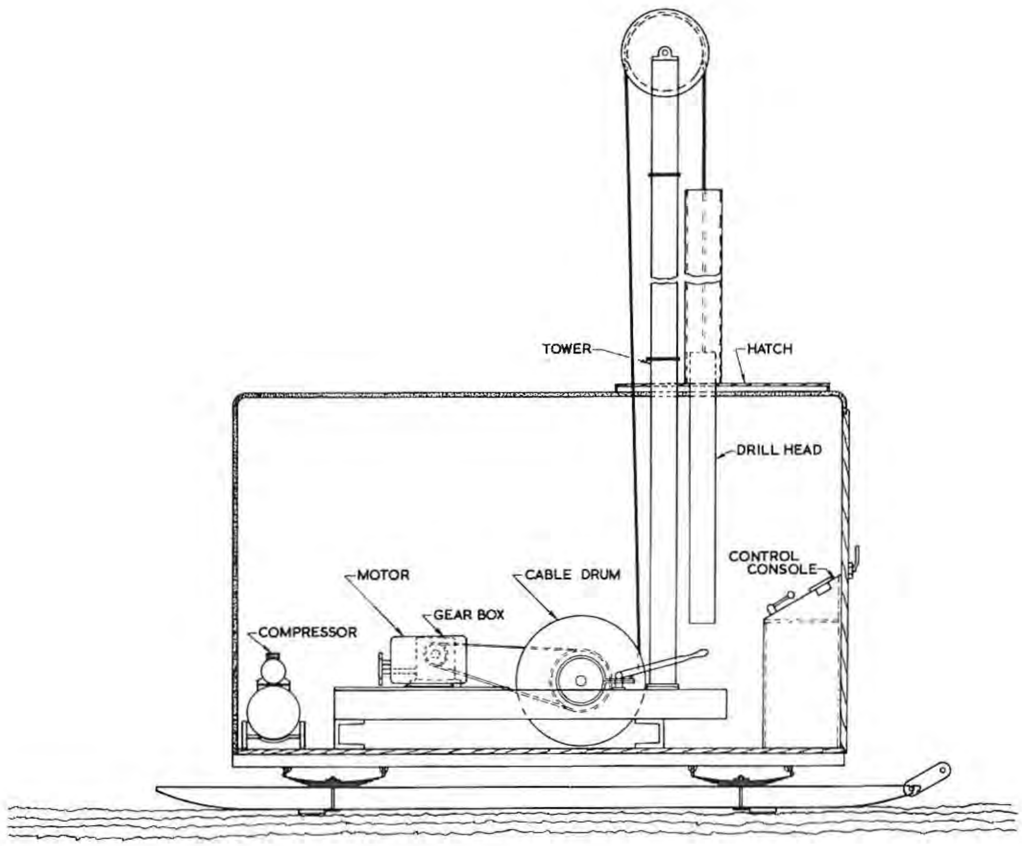


**Figure 2.** Schematic diagram of drill caravan assembly.

cludes extraneous materials and snow drift. The caravan chassis is shored with timber to support the winch assembly during drilling. Control and monitoring equipment is mounted in a console located adjacent to the drill tower (Fig. 2). A hatch in the caravan roof allows the tower to be lowered, then sectioned and housed in the caravan for transportation.

The caravan is made of 2.5-cm-square steel section, sheeted externally with light-gauge steel and internally with plywood; insulation is included in the wall cavity. Such a structure is lightweight yet is sufficiently strong to withstand difficult traverse conditions. Electrical heating near the control console provides a measure of operator comfort.

## The Drill Head

Proper functioning of the drill head ensures a plumb hole drilled at optimum rate. A malfunction can cause delays and accompanying complications due to borehole closure. For the new drill, the drilling process is monitored; thus irregularities are recognized early. Also the design of the heated annulus has been modified to make the consequences of failures potentially less catastrophic.

### The Heated Annulus

The efficiency of the drill is determined primarily by the rate at which the heat generated within the drill-head heater is conducted into the annulus and the ice face. It was found that cartridge elements previously used for heating the annulus had a number of undesirable features in practice, for example:

–the fine machining tolerance necessary for assembly of the cartridge units into the annulus;

–susceptibility to failure when immersed in water;

–multiplicity of vulnerable electrical connections;

–high cost;

–difficult to service.

For this reason a single element cast integrally with the aluminum annulus is now used (Fig. 3). It consists of three turns of standard 230-V sheathed heating element; dissipation is 3.9 kW. This arrangement has proved simple to manufacture, also efficient and rugged in operation. The transition area between the heated annulus and the core barrel is filled with a high temperature fiberglass-epoxy resin mix to maintain a uniform exterior profile.

The elaborate system described in an earlier report (Bird and Ballantyne, 1971) which aimed to protect the cartridge heaters and associated wiring from operational damage, proved tedious to manufacture and inefficient in operation. Inefficiencies arose from the thermal resistance which developed between the heated annulus and its surrounding shroud due to oxidation and distortion.

Although it was known that a drill-head heater consisting of a coil of bare resistance wire in direct contact with the ice face had proved highly successful (F. Gillet, personal communication, 1972), the 4-kVA voltage step-down transformer required could not be accommodated readily in the present drill.

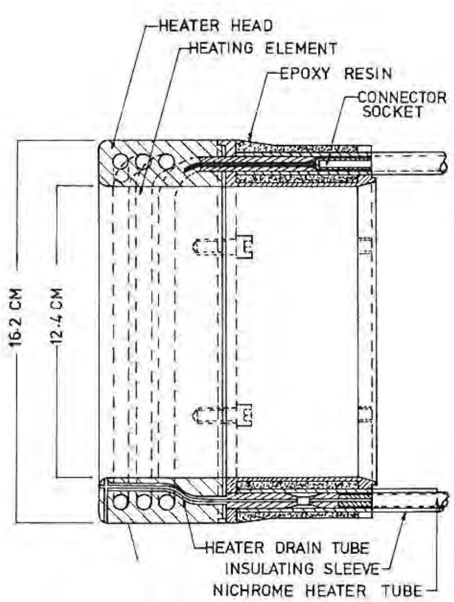


**Figure 3.** Heated annulus and core-barrel transition section.

### Drill-Head Monitoring Systems

Operational experience had demonstrated the importance of monitoring the drilling process, particularly factors associated with the removal and collection of the meltwater. Failure to remove meltwater from the drill face or to detect overflow of the meltwater tank can readily lead to "freeze-in" of the head, an ever-present danger associated with thermal drilling.

(i) *Vacuum monitor:* A melt-tank vacuum gauge has proved an invaluable monitor of drill performance; loss of vacuum, erratic operation of the vacuum pump and melt-tube blockages are readily detected. A solid-state vacuum transducer, "National" model LX1600A, provides a DC output voltage proportional to vacuum level; this information is monitored by a meter at the surface (Fig. 4).

(ii) *Melt-tank water level indicator:* Should the melt tank overflow, the excess water is ejected via the vacuum-pump outlet line; this water rapidly refreezes around and about the drill head. Freeze-in of the head is then inevitable. In the modified drill a water-level transducer is used consisting of a reed relay activated by a float-mounted magnet. The relay grounds the vacuum monitor line when the tank is filled and activates a "Sonalert" audio alarm (Fig. 4). This alarm facility allows maximum-length cores to be taken safely and guards against failure of the operator to empty the melt tank between drilling runs.

(iii) *Heated annulus temperature control:* Under certain operational conditions, such as hot shaving of the borehole, the heated annulus may lose, or maintain only partial, contact with the ice face; serious overheating and damage to the annulus can result. To guard against

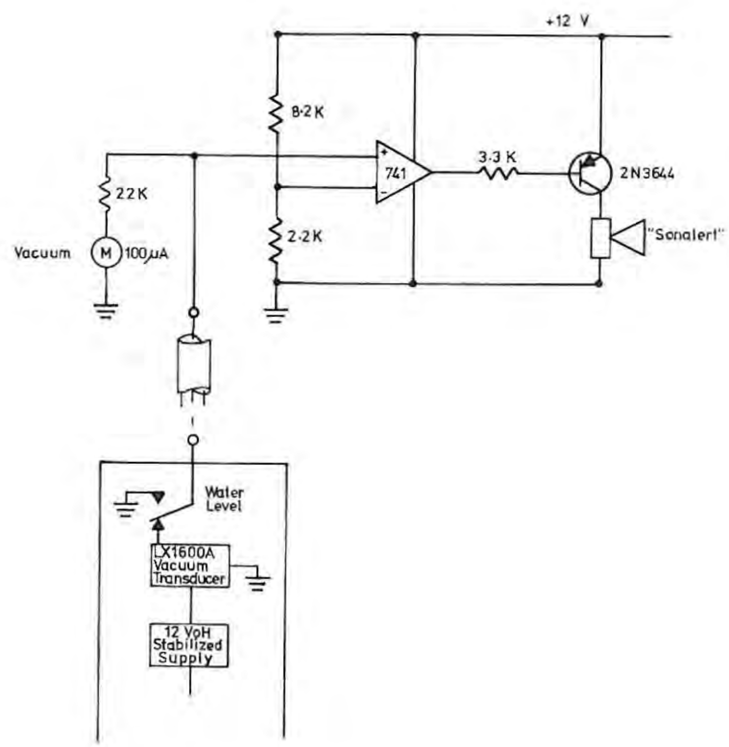


**Figure 4.** Melt-tank vacuum transducer and water-level alarm circuit.

overheating, thyristor control of the drill-head heater power and monitoring of the annulus temperature are provided.

(iv) *Borehole and core orientation:* It is important to know that a vertical hole is being drilled, also the orientation of the ice core.

A "Pajari" borehole surveying instrument, for the determination of azimuth and inclination, is mounted within the drill head. The instrument monitors the verticality of the borehole, and the orientation of ice cores with respect to the local magnetic meridian; it contains a timer for locking the instrument at a predetermined time during the coring process. Azimuth and inclination are measured separately by alternative orientation of the "Pajari" instrument.

A stylus mounted into the heated annulus grooves a reference line along each core; the line is easily related to the azimuth measured by the "Pajari" and forms a permanent record of core orientation in the drill head. The stylus retracts and does not hinder removal of the core.

### Winch and Control Equipment

The winch is powered by a variable-speed, reversible electric motor; speed control over a maximum range of 20-1 is achieved by thyristor control of the motor armature voltage. Electronic control allows a wide range of speed at rated torque, forward and reverse operation with dynamic braking, overload protection, and high reliability.

The average winch load is about 300 kg (drill head 90 kg and say 350 m of cable of weight 200 kg). On the basis of this load and the available electrical power, a 1.5-kW motor was selected. This thyristor-controlled motor at full load draws 2.7 kVA from the single-phase 230-V 50-Hz supply giving a maximum winching speed to the surface of about 20 m/min. For return of the head to the ice face, the free-wheeling speed is limited by braking, for safety.

An air-activated control is provided for the winch brake and clutch. This adds to the complexity of the original CRREL mechanical system but makes a worthwhile advance in operational convenience by allowing centralizing of the drill controls on a console. The variable-speed motor is coupled to the winch drum with chain-sprocket drives via the air clutch and a 40-1 worm-gear reducer. An air-operated dog-clutch disconnects the winch drum from the gear reducer for free-wheeling.

### Control Console

All controls and monitors are housed within a single control console. These include controls to the air clutch, air brake, winch motor and drill-head heater, also power metering, air control and drill monitors. The operator thus has full command of all the essential functions at one convenient location (Fig. 5).

### Air-activated Control of the Winch

The air clutch connects the motor to the winch drum gear reducer; a variable hand-controlled air valve allows smooth application of winch power via the clutch. Generous braking

**Figure 5.** Ice drill in operation, showing the winch, control console and operator.

capability is provided by a 25-cm disc brake; an emergency hand brake is within easy reach of the operator should the air supply or disc brake mechanism fail.

### Automatic Drilling Techniques

To drill a plumb hole at optimum rate, about 20 per cent of the drill-head weight should bear on the ice face.

The original CRREL design achieves this function by a calibrated suspension mechanism (Fig. 6) and a hand brake. The drill head weighs on average 90 kg and the suspension spring sensitivity is 8 kg/cm; two limit switches indicate the percentage of drill weight bearing on the ice face. The range 8-23 per cent is indicated by a green lamp, activated by the upper limit switch; range 16-30 per cent operates a red lamp via the lower limit switch. The winch drum was braked by hand to maintain the required drilling pressure, that is just within the red light end of the green light range (Ueda, 1966).

Manual drill feed proved tedious in practice, and with electronic control of the winch motor it became feasible to introduce an automatic servo-controlled feed system by switching the winch motor armature current with a relay activated by the lower limit switch. The drill head is gently lowered in approximately 5-mm increments, thus automatically maintaining correct drilling pressure for pendulum steering.

The great advantage of such a system is that the operator is free to perform routine core analysis and storage work during the 50-min coring period. Only cursory observation of the drilling is required during this period as the safety features outlined earlier adequately monitor the operation.

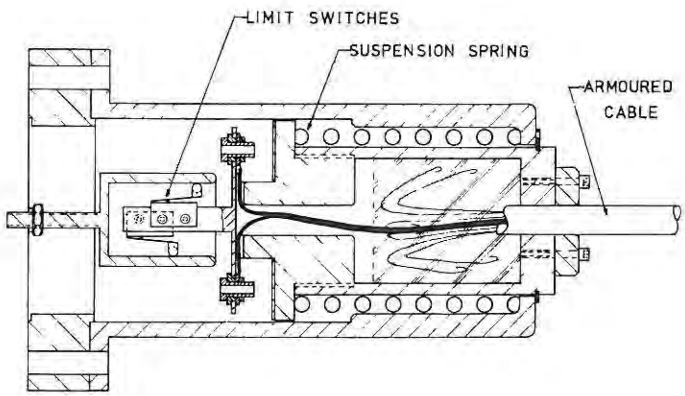


**Figure 6.** Drill suspension mechanism (also showing cable termination).

An alternative approach to automated drilling is to control the drilling pressure through operation of the air brake by the lower limit switch (Bird and Ballantyne, 1971). However, this technique can cause rapid acceleration and deceleration of the head, and provides a generally less satisfactory descent characteristic than is achieved using motor switching (K. Gooley and D. Russell, Antarctic Division communication from Casey Station, Antarctica, 1974).

### Thermal Drilling Experience

Except for the 310-m borehole drilled in the Amery Ice Shelf during 1968, all the Australian drilling activity has been undertaken in the Casey region, on Law Dome (Fig. 7).

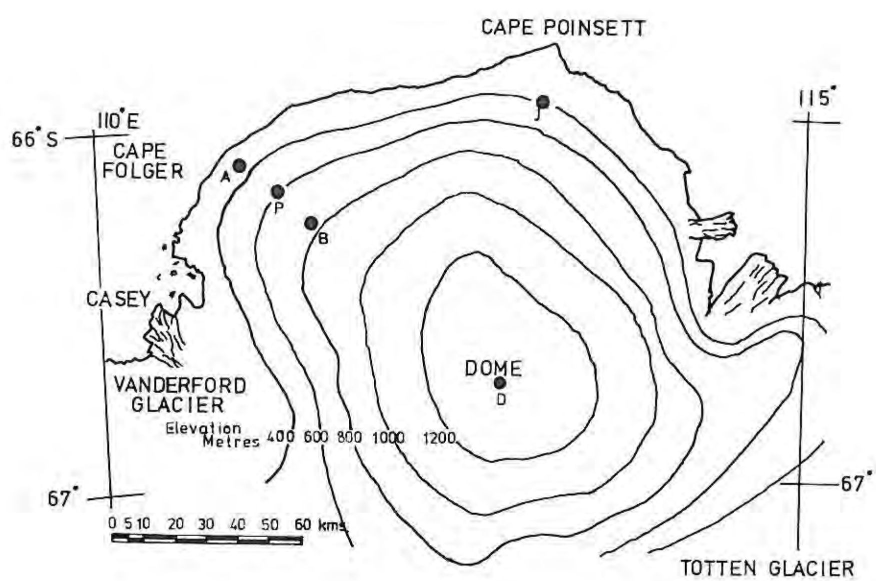


**Figure 7.** Map of the Casey region, showing the location of main drilling sites.

A summary of drilling operations during the period 1968-74 is given below (Table 1); discussion of these operational activities follows the summary table.

**Table 1**

**Summary of Drilling Operations**

| Location | Year | Borehole Depth, m | Drilling Period, weeks at site |
|---|---|---|---|
| Amery Ice Shelf: | 1968 | 310 | 20 |
| –Station G1 | | | |
| Casey: | 1969 | | |
| –Cape Folger | | 324 | 10 |
| –Law Dome Summit | | 385 | 3 |
| Casey: | 1972 | | |
| –Cape Poinsett | | 112 | 4 |
| –Strain grid B | | 73 | 1½ |
| –Strain grid P | | 113 | 2 |
| –Station S1 | | 53 | 1 |
| Casey: | 1974 | | |
| –Cape Folger | | 348 | 2 |
| –Cape Folger | | in progress | |

**Amery Ice Shelf**

The Amery Ice Shelf is of major interest as a monitor of outflow from the Lambert Glacier system. A segment of the 1968 Amery Ice Shelf project was to core two boreholes with a CRREL thermal drill at points G1 and G3, respectively 67 km and 240 km inland from the ice front.

It took five months overall to drill the 310-m hole at G1, delays being caused by inclement weather and drill malfunctions; loss of time and consumption of spares prevented drilling at G3. Major difficulties were caused by low temperatures, wind and snow drift; the lack of housing round the drilling rig was a significant factor in preventing operation in winds exceeding 12 m/sec. Meltwater pump malfunction caused the drill head to be frozen in at the 60-m level; it was finally recovered after several days of 450-kg cable tension and jerking, the application of several liters of alcohol and intermittent operation of the heaters.

The Amery experience clearly demonstrated the need for adequate housing of the drill rig, the desirability of automated drilling, the difficulty in removing unserviceable cartridge heaters from the head, and the need for telemetry of melt-tank vacuum and water level. Rubber vee-belts gave trouble at low temperatures, water and alcohol collected in the unsealed heater relay well causing relay malfunction, and cable twisting produced 200° of rotation over 60 m of drilling.

These problems, while causing consternation at the time, do not detract from the soundness of the CRREL thermal-drill concept. The fact that a borehole was successfully cored under such adverse conditions is a tribute to the drill rig and the tenacity of the four-man Amery team; closure finally prevented continuation of the drilling operation. In general the core quality was good, although there were problems due to shattering when cores were exposed to the thermal shock of -40°C and 10 m/sec winds. About 40 per cent of the cores were returned to Australia for analysis.

## Law Dome (Casey Area)

Since 1959, the Antarctic Division has been actively involved in glaciological study of Law Dome; the program includes thermal drilling at various locations (Fig. 7).

### 1969 Program

A drill of modified CRREL design was constructed during 1968 and successfully cored two holes in 1969. Core recovery from both boreholes was generally satisfactory, although a good deal of fracturing occurred. About 20 per cent of the core was returned to Australia for analysis, the remainder being stored near the drill sites.

Cape Folger was the first drilling site; work commenced on 19 May 1969 and concluded on 13 August. The program was delayed at the 150-m level from 12 June to 4 July due to illness of one of the four-man drilling party. Drilling proceeded normally to 324 m, where borehole closure became a problem and hot shaving was necessary to maintain drill clearance. This process, however, may have enhanced the creep rate, and eventually the drill made a new route at 232 m. Borehole closure could possibly also have been caused by horizontal shear of the hole. In general, the new drill performed well during this operation, most of the problems experienced at Amery Ice Shelf having been overcome. The automatic drill feed, the caravan housing and centralized controls were notably successful. Figure 8 shows an ice core being removed from this drill.

The Dome summit hole was commenced on 28 October and very good progress was made to 385 m in the ensuing three weeks. It took one hour to drill each core, using the automatic feed system, at an ice temperature of about -21.5°C. By 22 November both the melt-tank vacuum and water-level transducers needed, but were not given, maintenance. The drill became frozen in on 23 November.

Chronological events leading to the loss of the drill head and cable are listed below:

November 23 –0820 hours: At a depth of 385 m there were indications of probable trouble with the drill and the head was winched to the surface at 0900 hr. The pump flap valve was found open and thus meltwater was not collected for all or part of the period.

**Figure 8.** An ice core being removed from the thermal drill.

–0926 hours: The head was returned to the ice face for one hour of coring; the operator neglected to empty the previously collected meltwater.

–1010 hours: Trouble was suspected; the head could not be winched and was apparently firmly frozen into position. Cable tension to 2300 kg was applied immediately and 65 liters of alcohol was poured down the hole; the cable was vigorously jerked. The heaters were operated intermittently during the next 36 hours.

Review of these circumstances suggests that the melt tank overflowed soon after 0926 hr and meltwater was ejected over the top of the drill head.

November 25: A further 45 liters of alcohol was applied at 1030 hr and 1130 hr but there was no sign of loosening; the heaters short-circuited at 1050 hr. The drilling party then returned to Casey for additional supplies of alcohol.

December 4: 110 liters of alcohol was applied and the cable tensioned to 4000 kg periodically during the next 6 days.

December 10: There was no indication of movement in the drill head, and reluctantly the decision was made to cut the cable.

December 14: Explosive charges, comprising quarter-sticks of gelignite, were attached to the cable and dispatched to the base of the borehole. Six such charges appeared not to ignite; the seventh, however, jammed 15 m down the hole and severed the cable at this point. Thus, both the drill head and 370 m of cable were lost and the presence of the cable in the borehole prevented further measurement.

This series of events demonstrates the importance of drill-head telemetry, the likely consequences of failure to utilize it properly, and the need for effective cable-cutting equipment.

## 1972 Program

The principal aim of the 1972 program was to continue the core drilling studies by extending the coverage more widely over the northern survey triangle of Law Dome (Fig. 7, D, J, A). The program included drilling at strain grid J to bedrock, and H, G and B to at least 200 m.

(i) *Cape Poinsett:* Drilling commenced at Cape Poinsett (strain grid J) on 8 March. Beyond 30 m depth drilling speed slowed to 1 m per hour and core diameter decreased; at 50 m a partial failure was thought to have occurred in the winch speed control system reducing the torque output by 40 per cent. The cause of this failure was not established and inadequate winching power continued to retard the drilling operation although the 1.5-kW winch motor was obviously equal to the task. Continuous bad weather and minor malfunctions of the drill also caused problems; following one month of intermittent operation a depth of 112 m was reached. Borehole closure and curvature finally forced the abandonment of the site.

(ii) *Strain grid B:* Following overhaul of the drill plant at Casey during the midwinter period, drilling was recommenced at strain grid B on 23 August. The drill performed well; however, at 73 m a block of timber fell into the borehole and could not be dislodged. The borehole was abandoned.

(iii) *Strain grid P:* A borehole to 113 m was successfully cored at strain grid P commencing on 18 September but lack of winch power forced cessation of drilling at that depth.

(iv) *Station S1:* A 50-m borehole was drilled at S1 for future use in trials of carbon dioxide gas extraction equipment.

During 1972 four boreholes were cored and a total of 350 m of core was recovered; winch and heater head problems had precluded a more successful operation. An analysis of these problems during equipment maintenance in Australia revealed the following:

- the worm-gear reducer which couples the motor to the winch had no lubrication and transmission efficiency naturally was extremely low. Following replacement of a badly worn worm and wheel and the addition of correct lubrication, loads of the order 500 kg could be raised (maximum weight of the drill head and 500 m of cable is 450 kg).

- no fault could be found with the electronic speed control equipment.

- the thermal resistance between the annulus and shroud had risen significantly due to wear and oxidation; too little heat was being transferred to the drill face.

## Law Dome 1974

The 1974 program includes drilling to bedrock (390 m estimate) at a site 3 km upstream of the existing 324-m borehole at Cape Folger, also to drill at an additional site several kilometers further inland.

Drilling commenced on 14 March and reached a depth of 206 m within 10 days. Several minor problems occurred:

- the solid-state vacuum transducer failed because of voltage transients coupled between adjacent conductors within the drill cable; suppression cured this.
- the winch drum shaft failed at a flange weld.
- the insulation of the electrical connector at the heater head failed due to water immersion.

Operations ceased on 24 March pending repair of the winch drum shaft, drilling recommenced on 3 April, and continued normally to 348 m during the following 3 days. Borehole closure was becoming an increasing problem and shaving was commenced. During a traverse of the borehole the head jammed at 300 m and the heated annulus broke away when moderate tension was applied to the cable. Attempts to dislodge the annulus proved unsuccessful.

The heated annulus design shows it attached to the core-barrel transition section by six high-tensile 6.5-mm-diameter bolts tapped 20 mm into the annulus. However, for an unestablished reason short bolts were fitted during the assembly, possibly as a temporary measure, and these did not penetrate the tapped holes in the annulus. Therefore, only frictional forces held the annulus to the drill head and it was readily dislodged under moderate tension.

A further attempt at drilling to bedrock at Cape Folger is currently in progress.

### Borehole Logging Instruments

Instruments for the study of borehole deformation and temperature gradient are important adjuncts to the coring operation. The Division's borehole instruments and associated winches, control equipment and instrument rack are housed within a caravan of similar design to that provided for the ice drill. Two multistrand polythene cables are used for telemetry of the borehole data. The cable drums are powered from a variable-speed electric motor via an automotive differential; this arrangement allows drive to either drum by simply braking the other. Slip rings have not been provided on the winch drums and at selected depths the indicating instruments are plugged to the cables. However, there may be requirements for continuous profiling, for example of borehole diameter, and the feasibility of radio-frequency telemetry from the borehole instruments is under assessment. The major advantages of an RF system are that only a single strain cable would be needed and slip rings could be avoided.

### Inclinometer

For the determination of borehole movement, precise measurement of inclination changes up to several degrees is needed. Near the bedrock in coastal regions, the ice temperature can approach pressure melting and inclination changes of up to $20^{\circ}$ per year may occur. Measurement accuracy is required to be at least $0.1^{\circ}$ and preferably $0.01^{\circ}$, although such precision is difficult to achieve repeatedly in a practical borehole because of sidewall ripple and variable diameter.

The inclinometer described here is a 1-m-long brass tube, 6.25 cm diameter fitted with motorized retractable arms for positioning the tube within the borehole, and a "Schaevitz" angle deviation sensor, model LSRP, mounted within the tube. Its two orthogonal gravity referenced sensors have a range of $\pm 5^{\circ}$ and a resolution of 1 second ($0.00028^{\circ}$). An "Aanderaa" electrically activated magnetic compass, model K700, mounted at the base of the inclinometer, indicates azimuth to an accuracy of approximately $2^{\circ}$ (Fig. 9). Output voltage from both the angle deviation sensor and azimuth compass is displayed on a digital voltmeter; the digital resolution limit of the inclination measurement is $\pm 0.001^{\circ}$.

To achieve the desired $0.01^{\circ}$ *in-situ* measurement accuracy, strict tolerance restrictions must be held on the machining and assembly of the inclinometer positioning system. The arms are driven into position by a DC motor powered from a constant current supply; the motor may therefore be held in a stall mode. A shear pin holds the worm gear to its shaft and allows the arms to be collapsed should the motor fail.

An alternative approach suggested by H. Krebs (personal communication, 1972) is to mount the angle deviation sensor within a long (2-3 m) heavy tube which will tend to lie naturally along the sidewall of the borehole for even small inclinations; the complication of precision retractable arms is then avoided. Such an arrangement is presently under trial at Casey.

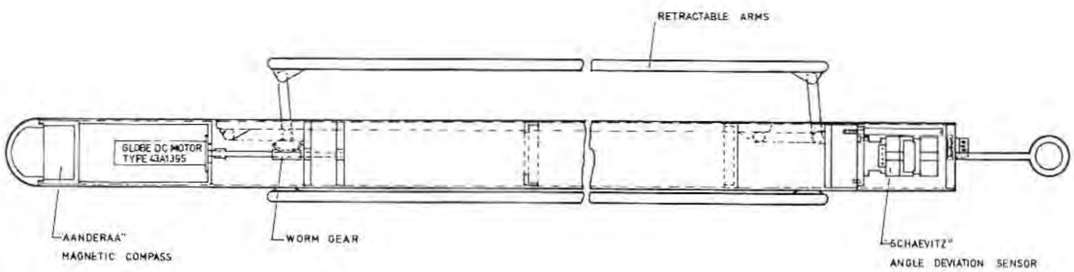


**Figure 9.** Borehole inclinometer.

### Diameter Caliper

For the borehole caliper, three spring-loaded arms provide the positioning force; a measurement resolution of order 1 mm is achieved. The 25-cm arms serve to average the effects of borehole ripple on measurement accuracy. A linear resistance transducer, coupled to a reference voltage, provides a DC voltage output proportional to borehole diameter (Fig. 10). Diameters in the range 7.5-18 cm can be measured.

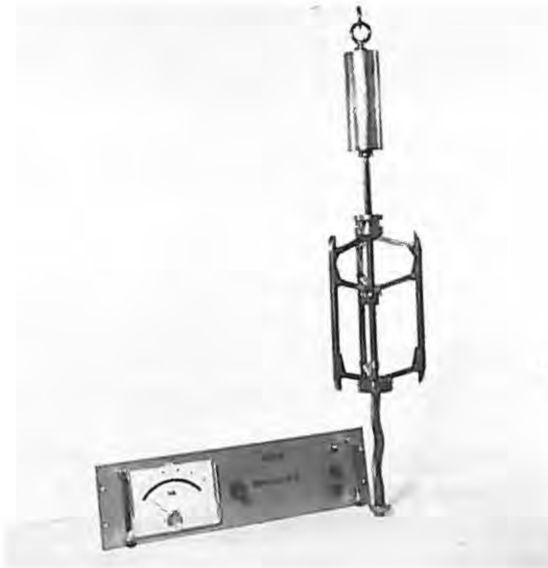

**Figure 10.** Borehole diameter caliper.

The caliper is fitted with a prototype radio-frequency telemetry system. A voltage-frequency converter allows the caliper DC output voltage to modulate a 100-MHz 50-mW transmitter. The RF signal will be detected at the surface, reconverted to a voltage, and monitored on the digital voltmeter.

### Temperature Probe

Borehole temperature measurements, to an accuracy of 0.01°C, are made using a specially calibrated "Hewlett-Packard" model 2801A quartz thermometer. The temperature sensor must be firmly held against the sidewall of the borehole by an arrangement which does not add significantly to thermal inertia. A protective cap pressed over the sensor end prevents wear due to sliding contact with the borehole.

The temperature probe comprises three lightweight phosphor-bronze spring arms, the sensor being attached to one of these arms by a fingered clamp (Fig. 11). A period of 15 minutes is required for an adequate cooling curve to be plotted and so establish the borehole temperature. The cooling curve is obtained from the quartz thermometer digital output by converting it to an analog voltage and plotting on a chart recorder. End-point temperature may then be readily extrapolated.

### Conclusion

The thermal drilling technique has now reached the point where moderately deep boreholes can be drilled almost with certainty and in relative comfort.

The operator may now be well protected from the elements and the automatic feed system

**Figure 11.** Temperature probe mount.

makes the task far less onerous than in the early stages of development. In addition, the various protective devices which can be incorporated into the drill remove many of the hazards formerly associated with thermal techniques.

**Acknowledgments**

The major contributions of CRREL in the development of thermal drilling techniques and the ready assistance given to the Antarctic Division through the good offices of Messrs. B.L. Hansen and H. Ueda are acknowledged.

The work of the Amery Ice Shelf Expedition, under very adverse conditions, laid a firm foundation for the continuing work on Law Dome. A number of expedition glaciologists and engineers have contributed to the project: Messrs. M. Corry, N. Collins, A. Nichols (Amery Ice Shelf), and R. Anderson, S. Little, C. Austin, M. Rich, D. Russell, K. Gooley (Law Dome). Mr. J. Ballantyne was responsible for the detailed mechanical design; the drill was constructed at the Division by Messrs. J. Nisbet and W. Kahrau.

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