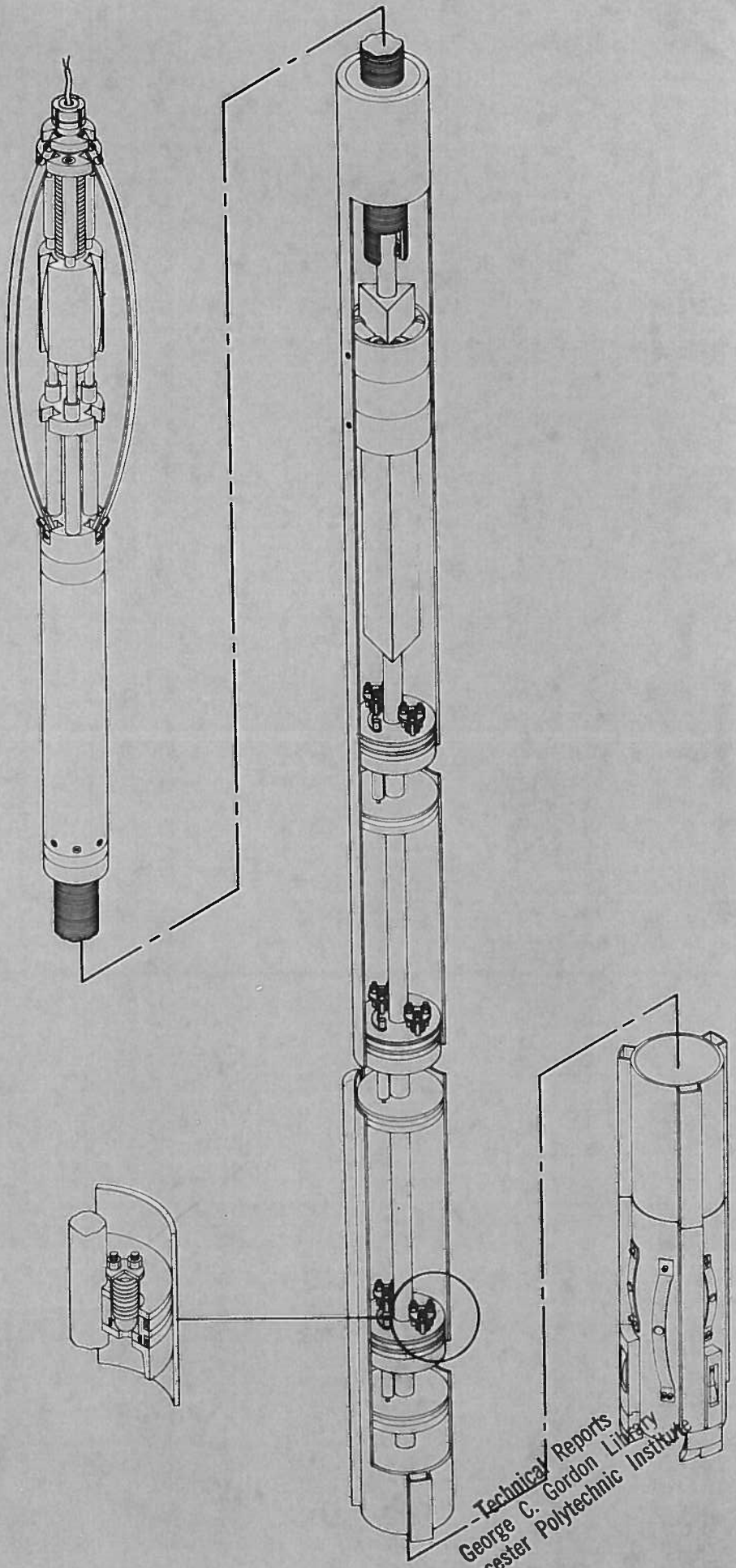


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Special Report 84-34
December 1984

**ICE
 DRILLING
 TECHNOLOGY**

EDITORS
G. Holdsworth
K.C. Kulvinen
J.H. Rand



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ICE DRILLING TECHNOLOGY

EDITORS

G. Holdsworth

K.C. Kulvinen

J.H. Rand

**Proceedings of the
Second International Workshop/Symposium on
Ice Drilling Technology**

**Calgary, Alberta, Canada
30-31 August 1982**

**U.S. Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire, U.S.A.
Special Report 84-34
December 1984**

DEDICATION

These proceedings are respectfully dedicated to the following distinguished persons of the glaciological community:

*Dr. Henri Bader,
of Miami, U.S.A.,*

who laid much of the theoretical foundation for the planning of the deep drilling operations in the major ice sheets.

*Dr. A. P. Crary,
of Washington, D.C., U.S.A.,*

who, almost 15 years ago, encouraged us with the time honored words: "Drill, drill, and drill some more..." (Presidential address at the International Symposium on Antarctic Glaciological Exploration, Hanover, N.H., September, 1968).

*Mr. Heinrich Rufli,
of Bern, Switzerland,*

who, through outstanding dedication, advanced the technology of the "shallow" electro-mechanical drills, unselfishly helped other engineers develop their own version of the "Rufli-Rand" drill, and contributed to the success of the recent penetration of the Greenland Ice Sheet.

PREFACE

In November 1979, a questionnaire was circulated amongst the international ice drilling fraternity to determine if there was sufficient justification for holding a workshop/symposium on ice drilling technology in 1982, eight years after the first symposium was held in Lincoln, Nebraska. The response was generally favorable, and by April 1980 the first of four bulletins was circulated from Ottawa, Canada, to about 20 people. Because the International Glaciological Society was holding a symposium on applied glaciology in Hanover, N.H. in late August 1982, it was considered that a convenient time to begin the workshop would be immediately after this meeting.

Because the idea of holding a drilling workshop was originally tabled at a meeting of the National Research Council Subcommittee on Glaciers in Ottawa in 1979 and because other members of that committee were available for advice, and support, the workshop was registered as an official activity of that subcommittee. While they were not finally able to participate in the workshop activities the following people offered their advice in the formative stages: G. K. C. Clarke, R. M. Koerner and W. S. B. Paterson.

The handling of submitted abstracts at the end of 1981 was ably carried out by B. L. Hansen, M. Mellor and J. Rand in the temporary absence of other persons on the papers committee. Karl Kuivinen helped extensively with pre-workshop preparation and at the meeting chaired several sessions, together with R. L. Cameron and G. Holdsworth. V. Bogorodsky offered his advice in the formative stages and

acted as the contact for his Soviet colleagues, who collectively submitted nine abstracts, but none of whom were finally able to attend the workshop.

Twenty-five people from seven countries attended the meeting held at the University of Calgary, in Calgary, Alberta, Canada from August 30 to noon on September 1, 1982. The list of attending registrants is given in an appendix. Of a total of 29 abstracts received, nineteen papers were finally presented. This was the result of the absence of persons from the Soviet Union, and Australia who faced insurmountable travel difficulties at the eleventh hour. However, it was possible to obtain manuscripts from some of these authors in time to include them in the proceedings.

Support for the workshop came from Environment Canada in the form of a contract to the Arctic Institute of North America (administered by the Canadian Corporation of AINA and an institute of the University of Calgary) through which arrangements were made for dormitory space and the lecture hall. Additional support came from Dome Petroleum, Calgary, and through registrants fee.

Manuscript preparation on camera ready format sheets was largely the responsibility of authors except for non-English contributors, who in some cases submitted unedited material. The editing and typing for these papers was done in Calgary.

G. Holdsworth
Environment Canada
Calgary, Alberta
September, 1982

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INTRODUCTION

Ice drilling has recently entered a very active phase, involving, on the large scale, international cooperative efforts. Some of the hardware has been derived and developed from commercial equipment designed for drilling and coring in rock. The exceptions to this are the specially designed hydro-thermal and electro-thermal drills and corers, which have been developed on sound thermodynamic principles. The hydro-thermal, or hot water drilling jet method, which is also applicable to drilling in geomaterials other than ice, has met with great success in rapidly penetrating glaciers and shelf ice even at temperatures well below the freezing point.

The existing large array of different ice drill units, some hardly off the drawing boards, some still in active service, and some trapped in their icy graves, attest both to the ingenuity of their inventors, and to the foresight of the scientists who promoted their concepts.

Ice drillers rely heavily on new technological developments in materials engineering. However, if the problem of drilling through deforming ice into bedrock is ever confronted, ice drill engineers may be able to stimulate research into new materials or special devices. For deep drilling, either by electro-mechanical or electro-thermal techniques, emphasis should be placed on the utilization of materials with as high a strength/weight ratio as possible.

Until quite recently, most of the ice drilling activities were in support of research, such as glacier physics studies, climatic change investigations and special hydrological studies. Now, with the northward and ultimately the southward extension of exploration for

fossil hydrocarbons, it has been necessary for exploration companies to drill and core through multi-year sea ice, pressure ridges, ice islands and even through shelf ice. These undertakings are required in order to determine the material properties of floating ice for embedding instrumentation and for determining the magnitudes of the possible thrusts that might be exerted by moving ice on engineering structures.

When the first core hole was drilled to bedrock in Greenland in 1966, there began a whole new era of paleo-atmospheric research based on isotope chemistry and conventional ion geochemistry of the ice. Cores have also been used to study the processes of transformation of snow into ice and the subsequent development of crystal fabric which is known to strongly influence the creep rate of ice. The total gas and carbon dioxide content of ice below the pore close off density has been measured at different sites and at different depths to study the changes in atmospheric constituents with time. Air bubble pressures may also give clues to the original altitude of formation of the surrounding ice and to decode possible surge behaviour of glaciers. The hydrogen ion concentration (pH) of ice core has turned out to be a very significant line of research. Volcanic eruptions have left their signatures in the ice of cold glaciers. In Greenland ice core, it is possible to recognize most, if not all, of the major volcanic eruptions throughout recorded history, to detect some that were not recorded, and to extend the log of volcanic events beyond the dawn of written records. Such time series have an important bearing on modelling volcanism, which ranks in importance with earthquake modelling. Such time series also have

an important input to climatic research.

Boreholes have been logged for deformation (tilt, closure and vertical strain rate) as well as for temperature, natural radioactivity and for experiments on the sonic properties of ice. The first four parameters are important input to glacier flow models. The phenomenon of glacier surging, which is an unstable mode of glacier flow (ranking as a geohazard) needs to be studied much further and carefully modelled. If only a part of the Antarctic ice sheet surged (resulting in just a few meters sudden rise in sea level), the consequences could be serious for the populated coastal areas of the world.

Recently, access holes were drilled through the Ross Ice Shelf, Antarctica, by several quite different drilling methods, in order to study (1) what processes are taking place at the base of the ice shelf (2) the oceanographic processes occurring in the water beneath the ice shelf, (3) the nature of biological life in the water and (4) the type of sediment that occurs on the ocean bed, as a clue to the geological and glaciological history of that region. All these studies surely rank with other major research projects in the surficial geosciences.

Significant advances in knowledge can only be brought about by maintaining at the very least, the current or projected number of drilling operations, and, in the Antarctic, by drilling to bedrock in certain key locations. Cores extending to 4000 m depth there could yield decipherable climatic information extending back at least 500,000 years.

In addition, the logging of the borehole would yield information valuable to flow instability modelling.

On the smaller scale, in terms of ice depth, activities in the Arctic, related to resource exploration, demand a continuous development of drills and corers to meet special conditions and new requirements. The same may be true for the coastal Antarctic areas, as geophysical exploration is carried out there and recovery operations develop.

C.S. Benson, Fairbanks, Alaska
V.V. Bogorodsky, Leningrad, U.S.S.R..
R.L. Cameron, Washington, D.C.
G. Holdsworth, Calgary, Alberta
K. Kuivinen, Lincoln, Nebraska
H. Kohnen, Munster, West Germany
S. De Paoli, Calgary, Alberta

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AN OVERVIEW OF ICE DRILLING TECHNOLOGY

B. Lyle Hansen
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0200

Abstract

The significant advancements in ice drilling technology since the Ice-Core Drilling Symposium at Lincoln, Nebraska, in August 1974 are reviewed. Three examples are: the flame jet and hot water drilling through the Ross Ice Shelf in Antarctica and the deep core drilling at Dye 3 in South Greenland.

Introduction

The predominant application of ice drilling technology has always been the acquisition of cores for glaciological and hydrological research. Another major application has been the provision of access holes through glaciers, ice shelves, lake and sea ice covers.

Both of these applications have been reexamined for the period 1949 to date in order to determine the significant advancements in ice drilling technology since the 1974 Symposium on Ice-Core Drilling.

Review of Ice Core Drilling

MacKinnon's (1980) compilation and other data in the author's files have been used to construct Figure 1 which shows that 37,500 m of ice core have been drilled during the period 1949-1982, and that the level of activity in ice core drilling has remained high since 1974. The 17,300 m of core acquired during the period 1975-1982 is 46 percent of the admittedly incomplete total of core collected since 1949. How the core

was acquired, i.e., what kinds of drills and cutting removal techniques were used, and how much of the 37,500 m of core was acquired with each of the techniques are addressed below.

There are several types of manually-operated corers. The SIPRE coring auger uses auger flights on the exterior of the core barrel and the space between the core and the interior of the core barrel to transport cuttings to the surface. Although 51 percent of the sites were cored with the SIPRE auger, less than 8 percent of the core was obtained with it. A few coring augers similar to the SIPRE auger have been made -- a recent example is Koci's (1984a) lightweight hand auger. There have also been a few augerless manual corers which have very narrow kerfs; the cuttings are collected on top of the next core and in the clearance between the core and the core barrel. About 4 percent of the sites have been cored with manual corers other than the SIPRE and less than 1 percent of the core was obtained with them.

The coring auger has been adapted to or modified for use with a variety of power assistance ranging from hand-held electric drills or gasoline motors to exploration drilling equipment. These adaptations were used at less than 3 percent of the sites and account for less than 2 percent of the core.

Rotary drilling equipment ranging in size from backpackable diamond core drills to conventional rotary rigs rated for 1500 ft of 2 3/8-inch drill pipe has been used for core drilling in ice. Cuttings were removed using compressed air, brine, kerosene, diesel fuel, water

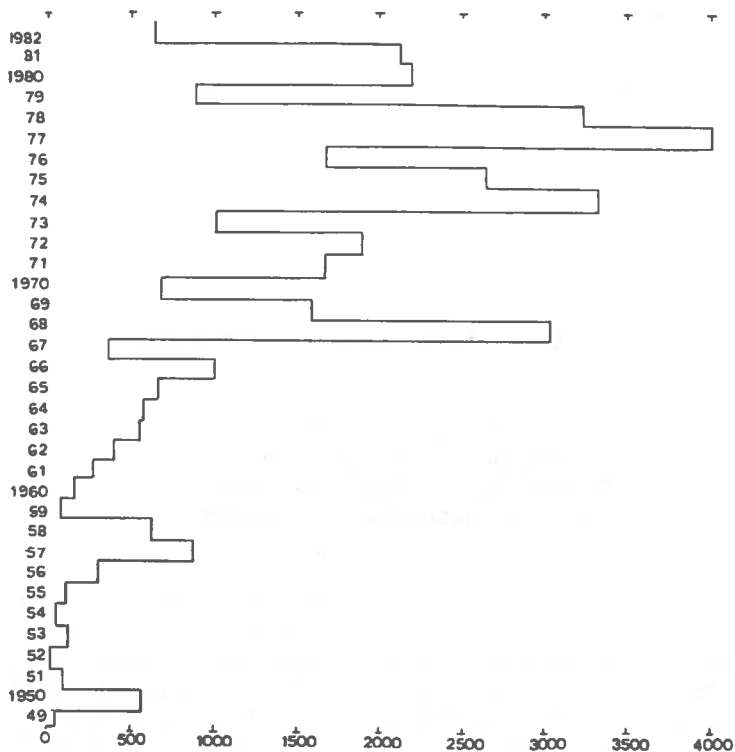


Figure 1. Meters of ice core drilling in the years 1949-1982.
The cumulative total is 37,500 m.

and reverse air vacuum circulation. Core barrels which required tripping the drill rod or pipe string for each core recovered were used more often than the wireline core drilling technique. Rotary drilling equipment was used at 5 percent of the sites to obtain 9 percent of the core.

Thermal core drilling was used at 23 percent of the sites to acquire 55 percent of the core.

Electromechanical corers are cable-supported core drills whose cuttings are removed by several methods depending upon whether the hole is dry or filled with liquid. In dry holes the auger flights on the rotating inner core barrel lift cuttings into a storage space above the core and retain additional cuttings between the inner core barrel and the non-rotating outer barrel or flight sheath; see Rand (1976), Rufli

et al. (1976) and Litwak et al. (1984). A similar construction was used by Theodorsson (1976) to drill through firn and on into a water-filled hole in the solid ice. In the electrodrill, Ueda (1969), the cuttings were dissolved in an aqueous ethylene glycol solution below the immiscible and lighter hydrocarbon liquid used to prevent hole closure. In the Danish "ISTUK" drill, Gundestrup et al. (1984), the slurry of cuttings and the liquid used to prevent hole closure was pumped by pistons into storage spaces above the core. Electromechanical corers were used at 13 percent of the sites to recover 24 percent of the core.

Having examined the percentage of core obtained by different kinds of drills and techniques let us look at the distribution (Table 1) by number of holes and depth. For this purpose the depth

Table 1

Type of Drilling	Depth Range (meters)	Percent of Holes		Percent of Core	
		1949-82	1975-82	1949-82	1975-82
Manual	0 - 20	52.1	56.5	8	5.7
Intermediate	20 - 500	46.0	41.1	64	60.8
Deep	> 500	1.9	2.4	30	33.5

interval 0-20 m is arbitrarily designated manual core drilling, the interval 20-500 m as intermediate and anything over 500 m as deep drilling. The distribution during the period 1975-1982 is essentially the same as the distribution during the period 1949-1982.

Advancements in Ice Core Drilling

Mellor and Sellman's (1976) General consideration for drill system design and Mellor's Mechanics of Cutting and Boring Part II (1976), Part IV (1977) and Part VII (1981) provides a rational basis for improvements in ice coring equipment and a measure of the efficacy and efficiency of the various drilling techniques.

Reeh's Antitorque Leaf Springs (1984) is a guide for the rational design of antitorque leaf springs.

The antitorque springs on the Danish shallow drill, Johnsen et al. (1980) and on their deep core drill, Gundestrup et al. (1984), were made in accordance with Reeh's design.

Suzuki's (1984) solution to the antitorque problem is unique and ingenious. He cuts four grooves along the hole wall. Fins above the cutters and the cutters provide the antitorque reaction to the coring bits. The vertical thrust of the side cutters can either increase or decrease the thrust on the core barrel.

Improved core bit cutter design lowers the driving and reaction torques required to cut ice cores. Improved core dog design greatly reduces the force required to break cores, permitting lighter-weight cables, towers and winches.

Both of these improvements have been demonstrated in recent electro-mechanical core drillings: see Gundestrup et al. (1984), Holdsworth (1984), Koci (1984c) and Suzuki (1984).

New developments in the removal of drill cuttings from liquid-filled holes have been included in three core drills. In the Danish "ISTUK" drill the slurry of cuttings and the liquid used to prevent hole closure is pumped by pistons into storage space above the core. In the French electro-mechanical drill, Donnou et al. (1984), the slurry of cuttings and hole fluid is centrifuged to separate the cuttings from the hole fluid. The cuttings are transported to the surface inside the centrifuge basket. The French, Gillet et al. (1984), also

developed a small diameter electro-mechanical core drill in which the cuttings were filtered from the hole fluid and transported to the surface inside the filter.

Thermal core drilling in a liquid-filled hole in cold ice can only be done if the meltwater is removed from the hole or mixed with another liquid to form an aqueous antifreeze solution whose freezing point is equal to or less than the ambient ice temperature.

Removing the water by pumping it through heated tubes into a heated meltwater tank for transport to the surface was first accomplished at Camp Century in Greenland in 1963-64, Ueda and Garfield (1968). Variations of this technique are still being used in Antarctica at Dome C, Donnou et al. (1984), and at Vostok, Kudryashov, et al. (1984).

Mixing the meltwater with another liquid to form an aqueous antifreeze solution is a technique which has been used in thermal ice core drilling for about ten years. Bogorodsky and Morev's paper (1984) describes the equipment and techniques for use on ice not colder than -33°C that was used by Zotikov et al. (1979) to core drill through the Ross Ice Shelf. The different equipment and technique required for ice as cold as -55°C is the subject of Bogorodsky et al. (1984) contribution to this symposium.

Another significant development is the use of electronics both at the surface and downhole for the measurement and control of drill functions. The outstanding example of this technology is the Danish deep drill system. The French "Climatopic" Thermal Probe, Gillet et al. (1984), has a small telemetry section transmitting four measurements to the surface.

The Ross Ice Shelf Project (RISP) was the inspiration for three innovations in ice core drilling using rotary drilling equipment. It was the first time that a wireline core drilling system had been used in ice, the first time that reverse air vacuum circulation had been used in ice coring and the first time that lightweight composite drill pipe had been used.

The prospective use of these innovations was described in an earlier paper by Hansen (1976).

During the second RISP drilling season reverse air vacuum circulation was used to drill a 178-mm diameter hole through the firn and into the

impermeable ice. That portion of the hole was cased using 162-mm (6-inch) I.D. fiberglass-reinforced epoxy pipe. Core drilling continued using a 159-mm diameter core bit and normal circulation using a mixture of DFA and trichlorethylene to remove the cuttings from the hole.

The cuttings were removed from the drilling fluid by a rotary vacuum filter.

Advancements in Access Hole Drilling

No attempt has been made here to review the large variety of techniques that have been used to drill access holes in temperate ice and through lake and sea ice covers.

Three techniques were successfully used to provide access holes through the Ross Ice Shelf.

One of them is the subject of Bogorodsky's and Morev's (1984) contribution to this workshop. Its application on RISP was described by Zotikov et al. (1979).

The second technique is flame jet drilling. Browning et al. (1978) used a water-cooled flame jet drill to provide two access holes through the Ross Ice Shelf in December 1977. One of the holes was reamed with the flame jet drill to maintain a minimum hole diameter of 30 cm.

Several thousand liters of cooling water were pumped from the J-9 in situ water well each time the flame jet drill was used.

Oily soot from incomplete combustion covered everything passing through the access hole and the people using the hole.

In an attempt to alleviate this problem the hole was successfully reamed with hot water flowing at a rate of 20 l/min through a No. 1H7 spray nozzle made by Spraying Systems Company, Wheaton, Illinois.

The success of this hot water reaming resulted in a decision to examine the feasibility of using hot water as the third technique to drill access holes for the next season.

Yen's and Zehnder's (1973) paper "Melting heat transfer with water jet" provided data on the heat transfer coefficient from a water jet to melting ice. F. Müller's (personal communication, 1978) experience with hot water drilling in cold ice provided additional data confirming the feasibility, and Browning was awarded a contract to perform the hot water drilling for RISP.

The use of hot water to drill three access holes through the Ross Ice Shelf has been described by Browning et al. (1979) and Koci (1984b).

Napoleóni's and Clarke's (1978) paper "Hot water drilling in a cold glacier" and Taylor's (1984) paper "A hot water drill for temperate ice" are excellent references for anyone contemplating the use of this technique.

Verral's and Baade's (1984) paper "A simple hot-water drill for penetrating ice shelves" presents an ingenious solution to a problem which can develop when holing through the bottom of a floating ice sheet or shelf.

Availability of Drills and Drawings

With the possible exception of Koci's lightweight hand coring auger the equipment described and discussed at this symposium is a one of a kind item for which there is no commercial source of supply. Shop drawings, bills of material and procurement specifications are seldom available. However, it has been this authors experience that there is a free exchange of the available information and a ready willingness to assist one another.

Conclusion

Ice core and access hole drilling continues to be an active field with an influx of new participants who are improving the equipment and techniques in use.

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ISTUK

a deep ice core drill system

by

N.S.Gundestrup, S.J.Johnsen and N.Reeh
Geophysical Isotope Laboratory
University of Copenhagen
Haraldsgade 6
DK-2200 Copenhagen N
Denmark

Abstract: The ice core drill system used to core to bedrock at a depth of 2037.63 m near Dye-3 in South Greenland (65°11'N 43°49'W h = 2490m) is described. The drill is designed to provide good core quality and to be easy to maintain in the field. It is a probe type system, with the drill suspended on a 6.4 mm cable. The drill consists of two parts. An antitorque section prevents rotation of the upper part, containing the motors and the electronics. During drilling, the ice chips, produced by the cutters, are sucked into the lower, rotating part of the drill. The chips are transported inside the drill to the surface, where the drill is clamped to a 6 m tower and tilted to a horizontal position for easy core removal and drill cleaning. The cutters work like a plane, which reduces the cutting power and provides stable penetration, essentially independent of the load on the cutters. The drill is powered by a rechargeable battery pack, and is controlled by a microprocessor in the drill. The length and weight of the drill are 11.5 m and 180 kg, respectively. The tower and the winch including an electro-hydraulic pumpstation and 2500 m of cable weigh 900 kg total. Core length is about 2.2 m per run, and the weekly production is 120 m of 10 cm diameter core at 2000 m depth. The core recovery is better than 99.9%. Close to bedrock the hole deviates 6 deg from the vertical, and the temperature is -13°C (-20°C at surface). The hole is filled with a mixture of JET A-1 and PCE. The liquid is cleaned by a down borehole filter unit. The hole diameter is maintained with a reamer.

INTRODUCTION

Previously, 2 deep (exceeding 1000 m) ice cores to bedrock existed. One from Camp Century (1966) in Northwest Greenland (Ueda, 1968), the other from Byrd Station (1968), Antarctica (Ueda, 1969). The drill used to recover these cores was lost in 1969 (Garfield, 1976), and no deep ice core drill was then available. There was an attempt to make an oil-rig type deep drill, the wire-line system (Hansen, 1976), but development of this drill was halted in 1978. In recent years, a thermal drill capable of operating in

liquid filled holes has been made in the USSR (Zotikov, 1979), however the operating principles of this drill (thermal drilling in ethanol) limit the applicability of the core for analysis.

ISTUK SYSTEM

The objective was to develop a drill capable of penetrating the Greenland Ice Sheet to a depth of 3300 m at temperatures down to -32°C. The temperature of the ice would be so low that no melting occurs. The core quality should be as good as possible. In addition, the drill should be so easy to operate that inexperienced students could serve as operators. Thermal drilling was excluded because stress created by the thermal shock causes breaks in the core. Furthermore, a thermal drill consumes about 5 kW of power (Mellor, 1976), and transport of this amount of energy to a drill 3300 m downhole is difficult.

Two different mechanical systems were considered: the oil-rig type and the probe type with the drill suspended on a cable. It was decided to use the probe system for several reasons, mainly due to lower costs and the ease of making modifications in the field. Also, the cuttings had to be removed in order to allow drill penetration. In the drill used at Camp Century and Byrd Station, the cuttings were dissolved in glycol. This system is complicated, and therefore it was decided to remove the chips by pumping the cuttings directly into storage chambers in the drill.

The drill is powered through the drill cable using a battery in the drill as a buffer. Thus the average power consumption and not the peak power could be used in designing the drill cable. This reduces the cable dimensions by a factor of 10, because the drilling time is just 6 minutes compared to a typical run time of 1 hour, and the rest of the run time is spent in hole transit and maintenance at the surface.

In fact, this concept is so effective that power transfer capacity is second to mechanical strength in specifying the cable. A 6.4 mm cable can power a drill 3300 m downhole!

The drill is controlled from the surface, and it is considered important to transmit as much information as possible regarding the drill behavior from the drill to the operator. Production of perfect ice cores is not easy due to greatly varying pressure, temperature, crystal size and orientation. In order to handle this, the drill was considered an instrument designed to produce ice cores, and not just a tool to generate cuttings. Following this philosophy, one microprocessor was used in the drill, and another one at the surface. In this way, the operator was relieved from most trivial tasks, and could concentrate on the winch and high level drill control. As a consequence, an operator can be trained in just 3 days. In addition, the computers enhance the reliability of the operation. If the down borehole computer detects an abnormal condition that may endanger the drill, it unconditionally shuts the drill down and notifies the operator. After removing the error condition, the drilling continues.

The drill tower is a blown-up version of the hinged tower used in the Danish shallow drill (Johnsen, 1980). The idea is to tilt the drill when it is clamped to the tower. This brings the drill to a horizontal position at the surface for easy core removal and drill maintenance. In addition, the tower height is reduced to 6 m, or about half the length of the drill.

The drilling proceeds in 'runs', and every run consists of the following steps. First, the drill is lowered down the hole. When the drill touches the bottom, the lower part of the drill rotates, cutting away a ring of ice. The produced chips are sucked into storage chambers inside the drill. After drilling about 2.2 m of core, the rotation is terminated and a pull in the cable makes the core catchers break the core. The drill with ice core and chips is hoisted to the surface. After cleaning, the cycle is repeated. At a depth of 2000 m, one run takes close to 2 hours.

The upper part of the hole was cased by U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), using 10-ft. long steel tubes with an inner diameter of 178 mm (Rand, 1980b). In order to counteract the hydrostatic pressure of the ice, the hole was filled with a mixture of kerosene (Jet A1) and perchlorethylene (PCE).

Drill

The drill is sketched in Figure 1. The length of the drill is 11.5 m, and it cuts a hole with a diameter of 129.5 mm. The core diameter is 102.3 mm. The ice is cut with a plane-like system consisting of 3 aggressive knives backed by stopper shoes controlling the pitch. The produced chips are mixed with hole liquid and sucked into 3 channels on the outside of the drill. Each channel ends in a piston

pump acting in a storage chamber.

The upper part of the drill, including the antitorque system, pressure chamber with motors, and a screw at the lower end of the pressure chamber, is prevented from rotating by 3 leaf springs pressed against the hole wall. The cable is terminated with ball bearings in a weight inside the antitorque system to allow for rotation of the cable. The weight serves as a hammer, which can be used to break the core.

The drill has 3 independent piston pumps, one for each cutter. The pumping action is created during gradual changing of the distance between a disc clamped to the rotating tube and another clamped to a center shaft which is connected to the motor section. In fig. 1, the shaded parts are connected to the motor exit shaft. The motor rotations are transferred to the lower part of the drill, the drill barrel, through a hollow screw, a triangular shaft and a linear bearing. The roller nut on top of the barrel engages the external thread on the screw and creates a linear motion of the barrel. This changes the distance between the discs and creates the pumping action. The diameter of the pump is 100 mm which gives an effective volume of 7 l per chamber. With a core length of 2.3 m, the volume of the ice cut by each cutter is 3.8 l. The pitch of the screw is 4 mm, and the number of rotations is 234, giving a stroke length of 936 mm.

The triangle- and piston-section are connected with a 4 mm pin which protect the piston section in case of overload.

A position-operated ball valve has a dual function. When the chip chambers are at minimum volume before the start of drilling the ball valve vents the chamber. When the drill moves up after drilling, released air from the cuttings is vented through the same valve. A second ball valve acts as a safety valve. The released air cannot escape through the channel due to a flap valve at the inlet between the channel and the chamber (not shown on the figure). This valve prevents loss of chips through the channel.

The core chamber has an inner diameter of 104 mm and a length of 2.95 m, including the drill head. The maximum possible core length is 2.75 m. A filter in the upper part of the chamber collects ice chips floating in the hole liquid while lowering the drill down hole.

Drill head

A stable drill head was manufactured from a single piece of steel using the spark erosion technique. On the drill head (fig. 2), a total of 18 components are mounted, including: 3 cutters, 3 shoes, 3 channels, 3 core dogs and 6 leaf springs. The ice chips move up in front of the cutter, and are mixed with hole liquid and sucked into the channels. The leaf springs keep the cutters away from the joints in the casing.

The core catchers are dog-leg shaped. They are spring-loaded against the ice core. They are so

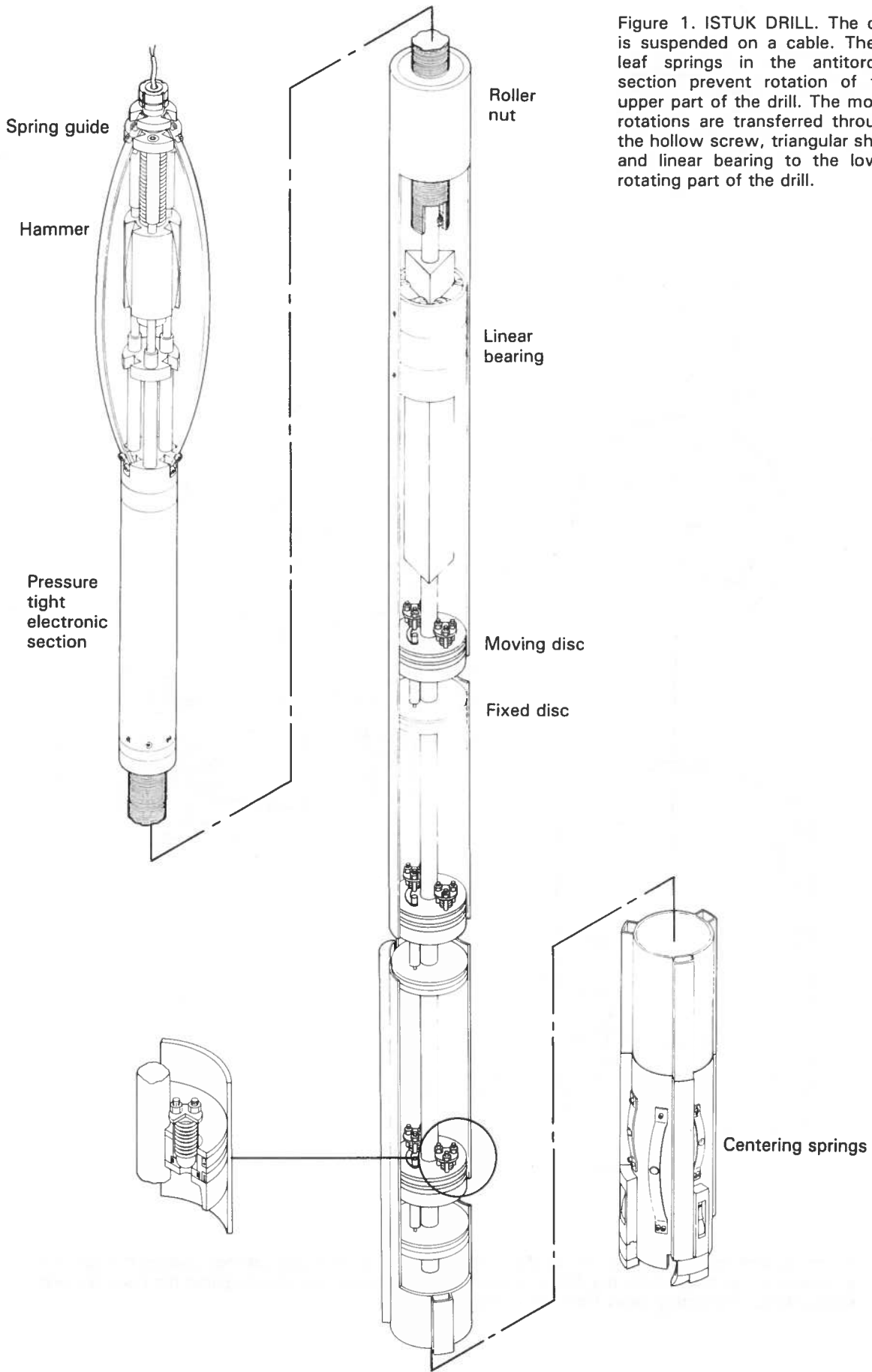


Figure 1. ISTUK DRILL. The drill is suspended on a cable. The 3 leaf springs in the antitorque section prevent rotation of the upper part of the drill. The motor rotations are transferred through the hollow screw, triangular shaft and linear bearing to the lower rotating part of the drill.

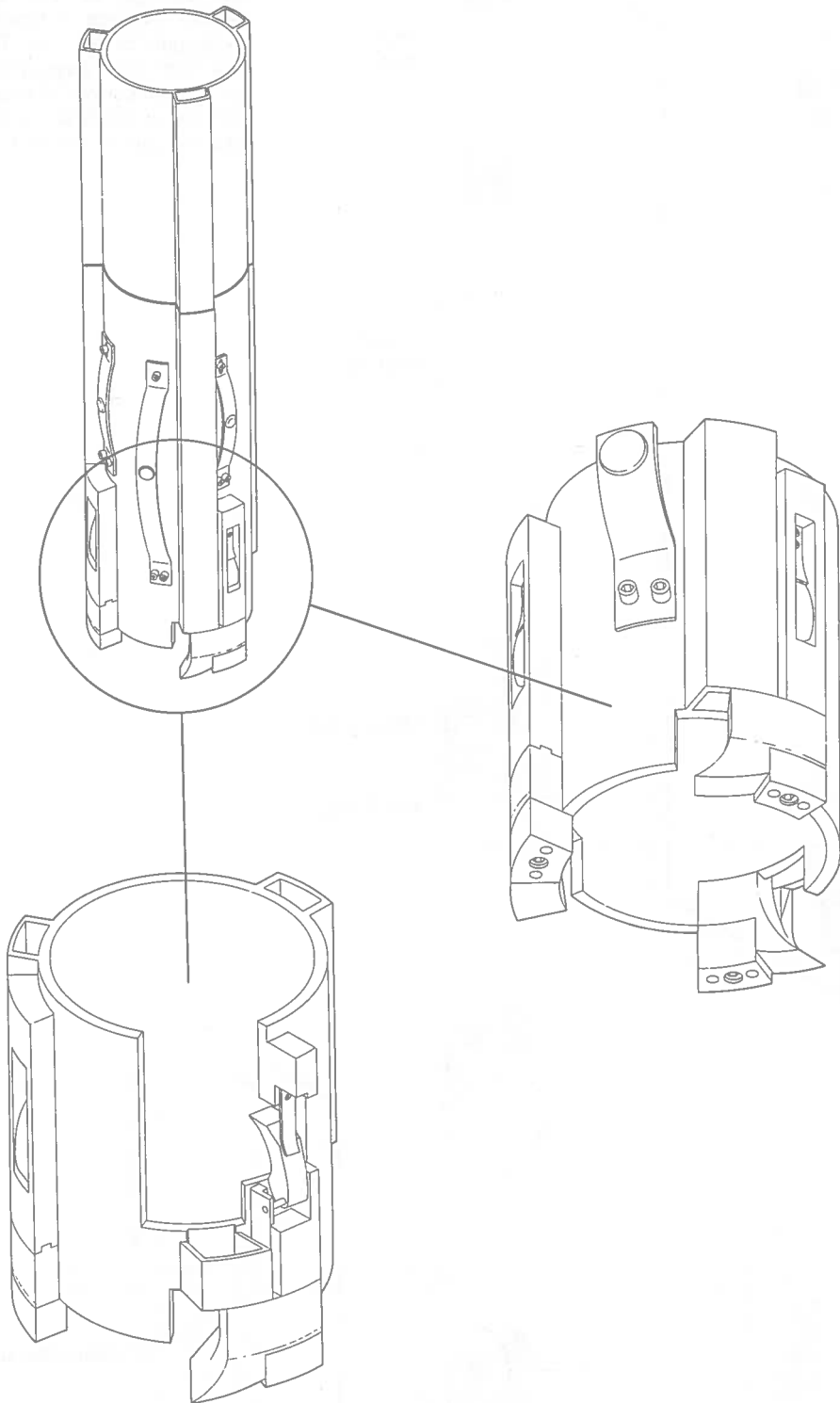


Figure 2. Drill head. The ice is cut by the 3 knives, and the produced cuttings sucked through the channels to chambers inside the drill. The core catchers are spring-loaded against the core. Six leaf springs keep the cutters away from the casing.

aggressive that they always worked. During the major part of the drilling, just two core catchers were used. The asymmetrical stress caused by two core catchers made the break easier than if three core catchers had been used. The natural position of the core catchers is the horizontal position. But the core catchers should have been spring loaded to ensure the upright position as the natural one. We found that if the core break left a slanted surface on the remaining core, then the core catchers would turn into the side of this surface when the drill started to rotate in the next run. The skew side then would break with a high probability of a lost run.

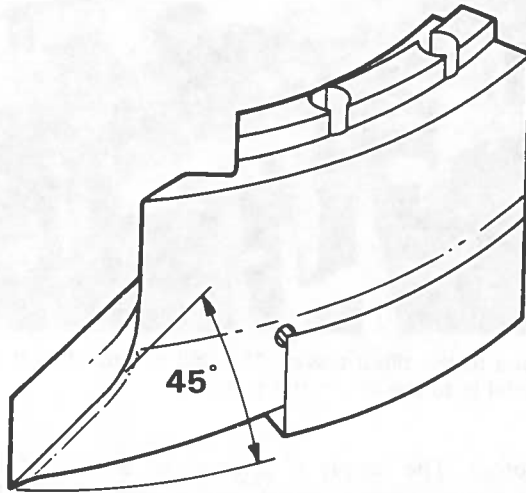


Figure 3. Cutter. The cutter works like a plane with the pitch controlled by a shoe behind the cutter.

Cutter

Each of three cutters (fig. 3) is mounted on the drill using a keyway and two screws. This mounting method is very rigid and ensures a constant core diameter of 102.35 mm. The front of the cutter is shaped to guide the chips into the channel. There is a 8.6 deg clearance angle between the cutter and the ice, and the forward cutting angle is 45 deg. With a pitch of 1.4 deg, the remaining 35 deg for the cutter is about the minimum due to mechanical reasons. All cutting edges, including those on the sides of the cutter, have a relief angle which reduces the power required to turn the bit and produces stable drilling characteristics. The shoe determines the pitch. These angles are not special for this drill, but are considered common to all electromechanical ice core drills used in cold ice. A plane cutting system does not require different cutters due to changes in ice conditions. By changing the 'shoe size', core length can be varied.

Pressure Chamber

All down borehole electronics, including motor and gear, are contained inside a pressure-tight steel tube

with an inner diameter of 100 mm. The tube is tested to withstand a pressure of 400 bars. Any leakage through the high pressure sealings is trapped in volumes between the high-pressure sealings and low-pressure O-rings. The pressure in these volumes is monitored by pressure transducers. In order to facilitate easy maintenance in the field, the electronics are constructed as stackable cylindrical modules. The modules, with plugs at both ends, fit together and a key ensures the modules are connected in the correct order. A total of four modules (power supply, computer, battery and motor power supply) are mounted on top of the motors, and a rubber spring between the upper module and the top pressure tube cover keeps the modules together.

Computer

The purpose of the down borehole computer is to monitor and control the drill operations. This includes charging and discharging the battery, keeping the battery temperature close to 20°C, monitoring four pressure transducers for any sign of leakage or outgassing of the battery, monitoring inclinometers for loss of antitorque, etc. A total of 30 analog parameters are measured. All measured values are compared to a limit. If this limit is exceeded, the computer takes appropriate action, and if it is a condition that may endanger the drill, the computer unconditionally shuts down the drill. After removal of the error condition, the drilling can continue. The drill communicates with the surface terminal using 300 Baud full duplex CCITT compatible audio tones riding on top of the supply current to the drill. Thus, just a single conductor coaxial drill cable is needed, and a commercial converter between the audio tones and digital signals (modem) can be used at the surface. The computer receives commands from the operator regarding drill speed, direction, etc., and transmits to the surface information on status, cutter load, motor current, battery current and screw position in addition to 27 other parameters.

Battery section

The major part of the energy required for the actual drilling is delivered by the battery pack. This consists of 55 pcs of 2 Ah 'SAFT' commercial C-size Ni-Cd cells heated to 20°C. The discharge current is about 7 A corresponding to a charge consumption of 0.75 Ah for a run. With a load current of 7 A, the capacity of the cells is at least 1.5 Ah.

Under normal use, the lifetime of a Ni-Cd battery is specified to 100 cycles. Hodge (1976) points out that the battery lifetime may in fact be several thousand charge-discharge cycles if the following conditions are observed: The battery temperature is kept close to 20°C, the battery is not too deeply discharged, the charging current for a 2 Ah cell is between 1 amp and 4 amp and the battery is never overcharged. The first 3 conditions are easy to fulfill, and overcharging is prevented by using

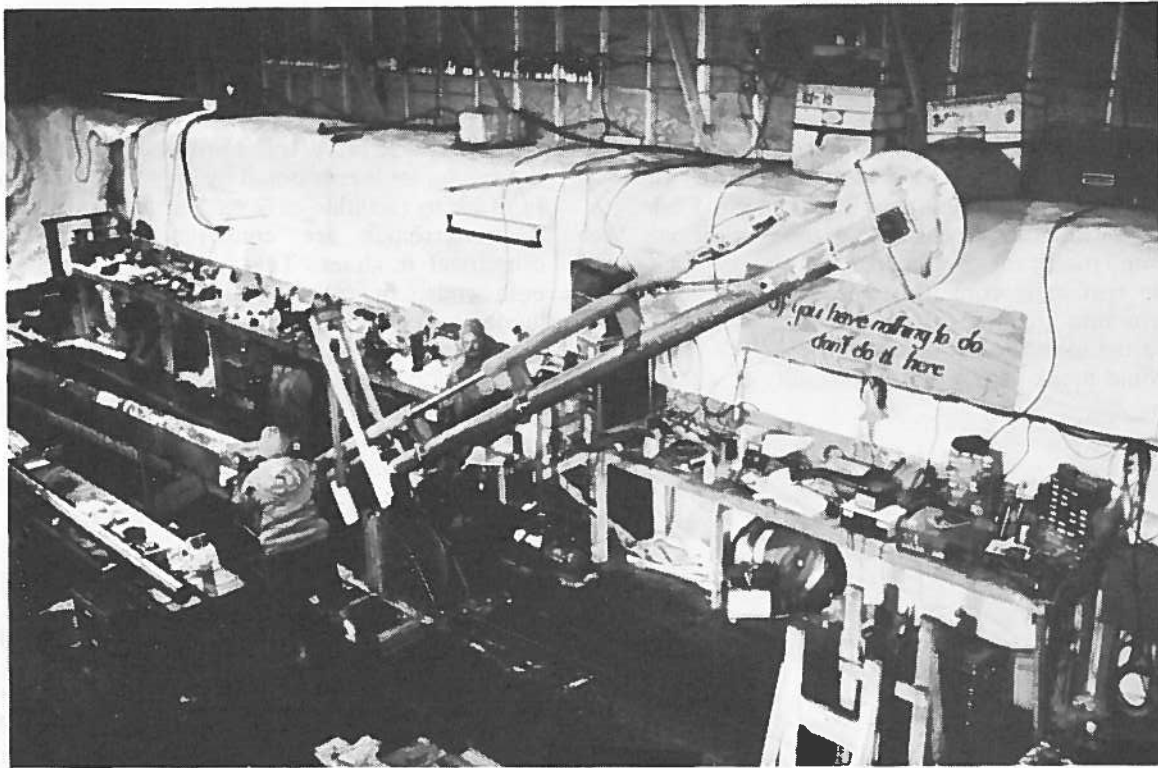


Figure 4. Drill shelter. The picture shows the drill clamped to the tilted tower. The drill is moved to the upright position for rewinding the screw. A spare drill barrel is to the left in the picture.

battery temperature, current and voltage to indicate the level of charge. Thus the down borehole micro-processor terminates the charge at the correct time based on the empirical equation valid for this cell:

$$V = 1.54 \cdot T \cdot 0.003 + I \cdot 0.015$$

V is cut-off voltage per cell in Volt
 T is battery temperature in Celcius.
 I is charge current in Ampere

This method is so effective that no battery failures occurred, nor did any sign of outgassing or battery deterioration take place (Klipstein, 1967).

The battery pack consists of 5 columns, each containing 11 batteries. A heavy copper foil is wrapped around the 5 cylinders to keep all cells at the same temperature. Two wire heaters are in thermal contact with the copper foil, and about 8 mm of insulating foam is moulded to the outside. The power required to heat the battery section from -20°C to +20°C is 25 W.

Motor Power Supply

The motor power supply converts the battery voltage (55 V to 85 V) to a variable voltage for the motors. Nominal output voltage is 48.5 V. This can be changed by the computer to 10.5 V, 38 V or the battery voltage. The polarity of the voltage can be reversed. The maximum output current is limited to 12 A, thereby limiting the maximum torque of the

motors. The supply is constructed as a very high efficiency (94%) switch-mode step down DC supply.

Motor-gear section

The drill motor is a low-temperature lubricated dual disc type DC motor (Mavilor type 81). The motor efficiency is 75%. On the shaft of the motor is mounted the Harmonic Drive gear (type 20-160-2A), which reduces the nominal 6000 rpm of the motor to 37,5 rpm in one step. Considering that the required lifetime of the gear during drilling is just 200 hours, the gear is lubricated with a low viscosity 10 cSt silicone oil, (Dow Corning Fluid type 200) which ensures high efficiency operation of the gear. Fine molybdenum disulphide powder added to the gear oil ensures sufficient lubrication. The number of rotations is limited by the screw to 234, corresponding to a drilling time of 6 min 15 sec with the nominal rotation speed of the motor. A shaft encoder is mounted on the motor. By counting motor revolutions, the computer calculates the screw position.

Below the gear, a ball-bearing section absorbs the static pressure on the exit shaft as well as the force created during core-break. This section is designed to withstand the cable breaking force of 25 kN.

If the screw should be blocked, the motor-gear section is protected against overtorque by a 6 mm pin which connects the exit shaft to the triangle section.

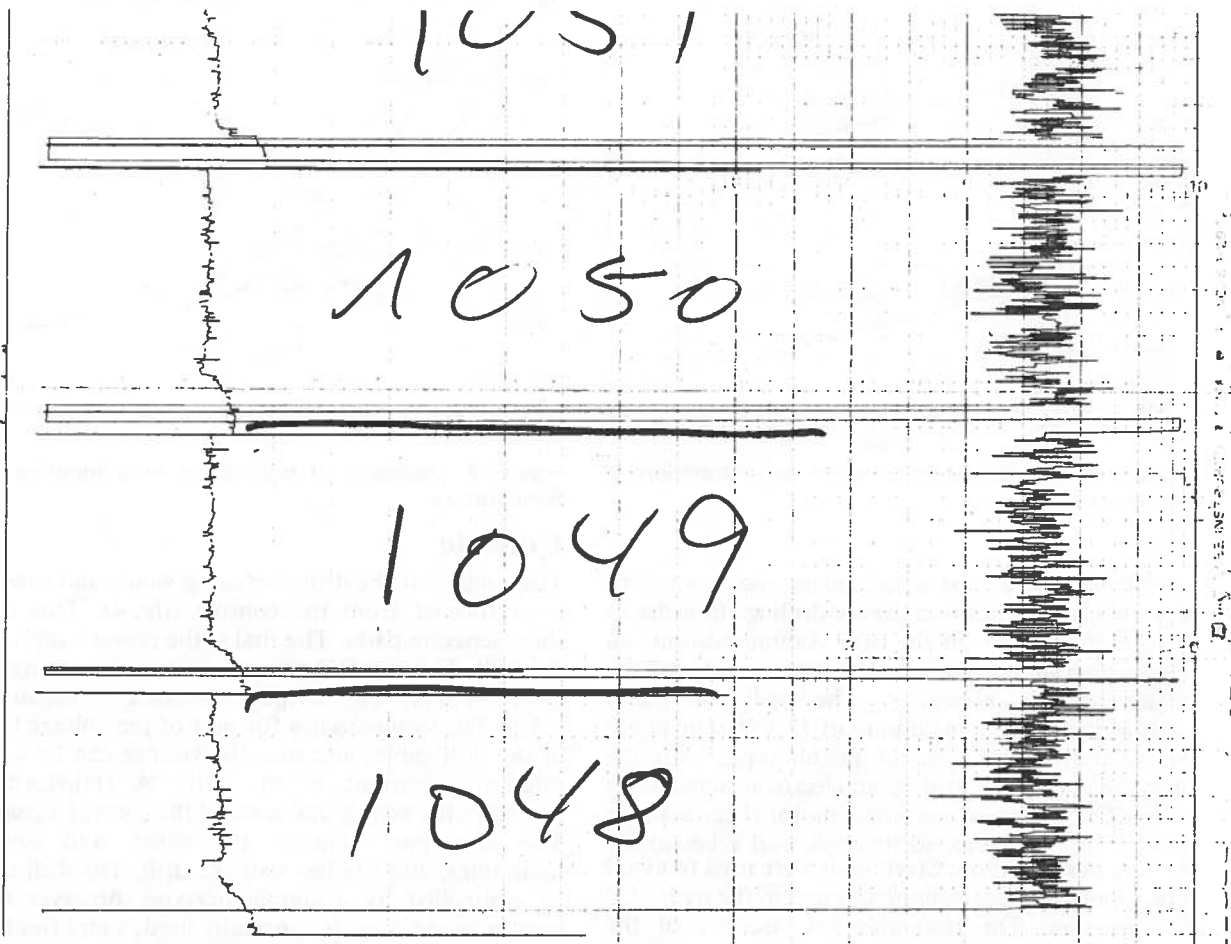


Figure 5. Plot of cutter load (left) and motor current (right) for some runs. The motor current is unaffected by cutterload.

Antitorque section

The purpose of the antitorque section (fig. 1) is to prevent the upper part of the drill from rotating relative to the hole wall, and at the same time to allow for vertical movement of the drill with minimal friction against the hole wall. The system is similar to that used in our shallow drill. Three leaf springs, spaced symmetrically around the drill axis, prevent the rotation. The springs are 2,5 mm thick, 20 mm wide and the distance between the supports is 690 mm. They are bent in a fourth-order parabolic shape in order to ensure a uniform load distribution along the 355 mm length of the spring in contact with the hole wall. The nominal radial force for each spring is 390 N, corresponding to a maximum bending stress in the spring of 760 MPa. The total antitorque section can produce a torque of 100 mN when the edges of the springs are sharpened.

The distance between the supports for the leaf springs can be adjusted by moving the upper support. A guide close to this support prevents rotation of the springs. This antitorque system is very simple, compact and rugged. Calculations for the springs are shown by (Reeh, 1982).

The cable, which is mounted in a steel hammer surrounded by the leaf springs, is attached in such a way that it allows the cable to rotate relative to the drill. The hammer can move 10 cm along the drill axis. The cutterload is determined by a spring on the upper 2.5 cm of this distance which combined with a linear transducer, measures the position of the hammer.

Cable

The cable is Rochester type 4H-252K. This is a steel-armored 4-conductor teflon-insulated cable. The diameter is 6.45 mm and the breaking strength is 24950 N. Weight in air is 153 kg/km. The resistance of the shield is 11.5 Ω /km, and the four conductors operated in parallel have a resistance of 16.7 Ω /km. The maximum voltage is 300 V DC. The maximum applied voltage is 200 V.

Winch

Winch requirements were for a nominal cable speed of ± 1 m/s and a minimum speed of a few cm/s. The depth position of the cable in the hole should be controllable to within a few cm. With these

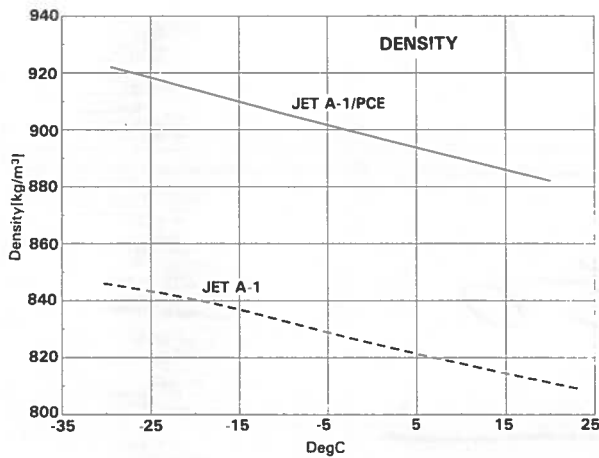


Figure 6. Density of hole liquid as a function of temperature.

specifications, no extra mechanism was needed to control the drill position during drilling. In order to avoid interference on the drill communication, an electrohydraulic winch was used in spite of its relatively poor efficiency. The hydraulic pump station consumed a maximum of 13 kW. The pump is a variable displacement piston type, with the displacement controlled by an electrical signal using a 'MOOG'-control. The winch motor (Danfoss type OMSS-160) is connected through steel tubes to the remote pump station. Steel tubes were used to avoid pressure-dependent volume changes in the hydraulic transmission. The recommended viscosity of the hydraulic oil is 73 to 37 cSt, with a minimum of 21 cSt. The oil is Mobil type Aero HFA. The same oil type was used in the Byrd Station drilling. Although this oil has very little change in viscosity with temperature, the viscosity was frequently less than 21 cSt, corresponding to an oil temperature higher than 24°C. The winch drum holds a maximum of 3500 m of 6.45 mm cable. The cable is positioned on the Lebus grooved drum by a guide wheel.

The maximum force from the winch is limited by an overpressure valve in the hydraulics to 8 kN, compared to a cable breaking force of 25 kN. This means that the winch is not able to break the cable even when operating the hammer in the drill. The absence or release of pressure on the hydraulic locks the winch.

Tower

The tower is hinged and can be tilted by a hydraulic piston. The piston is controlled by a small hydraulic pump through a proportional valve, allowing a variable tower speed.

The tower and winch are bolted to the ends of two 10*6-inch timbers, 25-ft long which are spaced 3-ft apart.

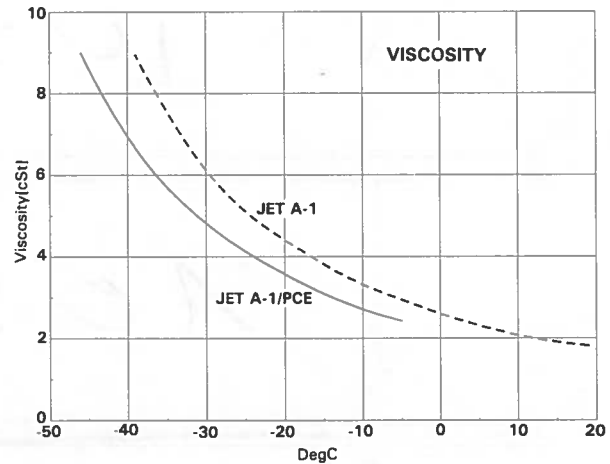


Figure 7. Viscosity of hole liquid as a function of temperature.

Console

The control of the drill, including winch and tower, is performed from the console (fig. 4). This has three separate parts. The first is the power supply to the drill. This is a DC power supply with a rating of 190 V, 2.8 A. The output resistance is negative, -33 Ω. This compensates for part of the voltage loss in the drill cable, and thus the voltage can be kept relatively constant at the drill. A transformer separates the supply current and the control signals. The next part controls the winch and tower hydraulics, and the last part the drill. The drill can be controlled by a simple teletype, however the computerized console, normally used, simplifies the operation to the extent that a student with no previous knowledge of the system, could learn to operate the drill after a few days. The computer used is an ABC-80, a relatively fast personal computer. It is interfaced to the depth counter, the drill modem, a dual channel analog strip chart recorder for recording cutterload and motor current, a digital printer and a TV monitor. The computer transforms the drill information, and provides a semi-analog display of motor current, cutter load and screw length on the screen, and tables showing 30 other parameters, i.e., drill penetration during a run, temperature, inclination etc. The operator controls the winch based on this information. Fig. 5 is a plot of cutter load and motor current for some runs. The cutter load decreases after the start of drilling, and then remains constant because the operator gives slack in the cable. The motor current is not influenced by the cutter load. This is typical for a plane-like cutter system. A constant motor current during a complete run indicates that there is no sticking between the core and barrel, and that the pumps are working correctly. In fact, the cutter load is negative because after the start of drilling, we pull in the cable to obtain a negative cutter load of about 500 N. Due to the aggressive cutters, this negative cutter load has no influence on the pitch and thereby the core length. The negative cutter load stabilizes and minimizes the drill inclination.

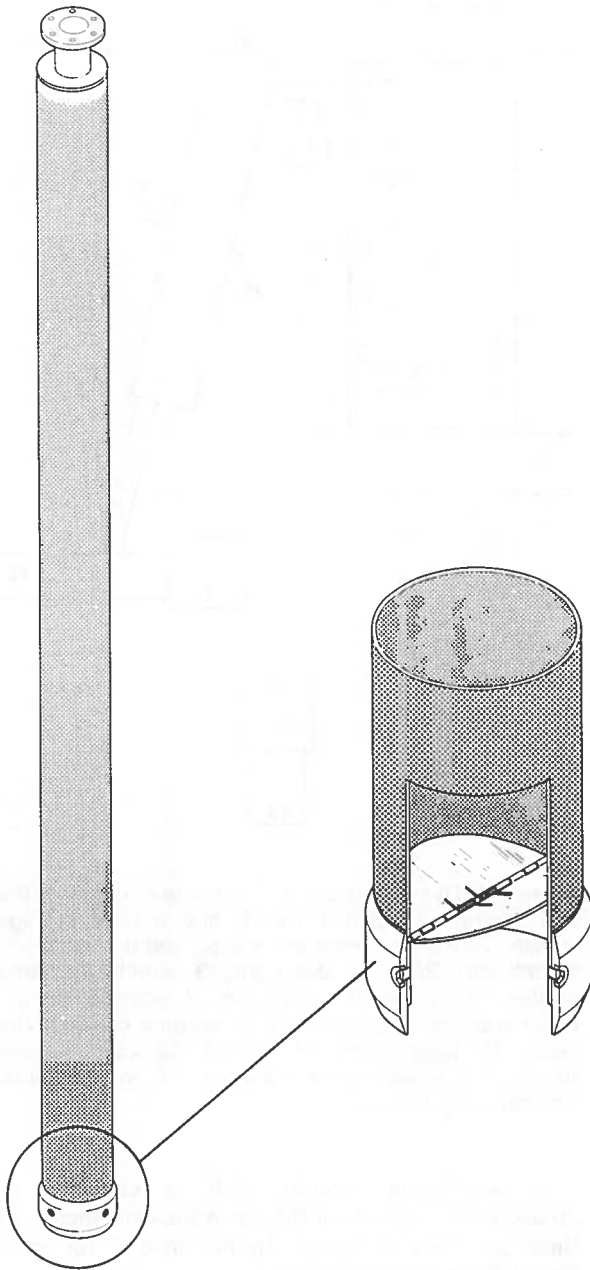


Figure 8. Downbore hole filter. The spring-loaded valves at the bottom of the filter (lower right) open when the filter moves through the hole liquid, collecting the floating chips.

Hole liquid

In order to compensate for the hydrostatic pressure of the overburden ice, the hole is filled with a liquid. This liquid should not react with the ice, the density must be close to 920 kg/m^3 , and the viscosity not so high that the winch speed is adversely affected. In the Byrd Station drilling, a mixture of kerosene (DF-A) and trichlorethylene was used. At Dye-3, Jet A-1 was used due to its specified viscosity at -20°C (Table 1) and its higher purity. However, the difference between the two fluids is small.

TABLE 1. Hole liquids

Properties	DF-A	JET A-1
Density (15°C) [kg/m^3]	770-840	775-830
Viscosity [cSt]	1.4-2.5/ 38°C	max 8/ -20°C
Vapour Pressure [mmHg]		max 0.4/ 10°C
Freezing Point [$^\circ\text{C}$] max	-48	-50
Flash Point [$^\circ\text{C}$] min	40	38

TABLE 2. Density adjusters

Properties	Trichlor	Perchlor
Density [kg/m^3]	1470	1620
Freezing Point [$^\circ\text{C}$]	-86	-23
Vapour Pressure [mmHg]	56/ 20°C	14/ 22°C
Flash Point [$^\circ\text{C}$]	32	not flammable
Boiling Point [$^\circ\text{C}$]	87	121

The density of the hole liquid was increased by the addition of 10% Perchloroethylene (PCE) to the kerosene. PCE was preferred over trichlorethylene because it is less toxic due to a 4-times lower vapour pressure. Furthermore, PCE cannot burn, and has even been used as a fire extinguishing agent. PCE freezes at -23°C , but that is no problem in Greenland during the summer. Both kerosene and PCE are very aggressive solvents. Thus, all gaskets must be either Teflon or Viton.

As shown in fig. 6, the density of the liquid varies with temperature. This must be corrected for when mixing the liquid. The casing leaked at the bottom, so in order to compensate for the missing 50m of liquid, the density of the hole liquid was increased to 950 kg/m^3 . The PCE freezing point of -23°C does not influence the mixture (fig. 7), so that could be used down to -50°C .

Filter

Not all of the cuttings are collected in the drill, and some ice is scraped from the hole wall by the cutters during hole transit. These chips were collected twice a week by a down borehole filter (fig. 8). The filter is bolted to the bottom of the electronics section after the screw and barrel are removed. When the filter passes down through the liquid, the spring loaded valves at the bottom open, and the chips are collected in the filter. As the density of the hole liquid is higher than that of ice, the chips float upwards in the hole, and just the upper few hundred meters of the hole have to be filtered. The high density also keeps the bottom of the hole clean. For these reasons, it is advantageous to use a hole liquid with a slightly higher density than the ice.

Reamer

The Dye-3 drilling was a multiseason operation, with 9 months between the field seasons. During this time interval, the hole had a tendency to close

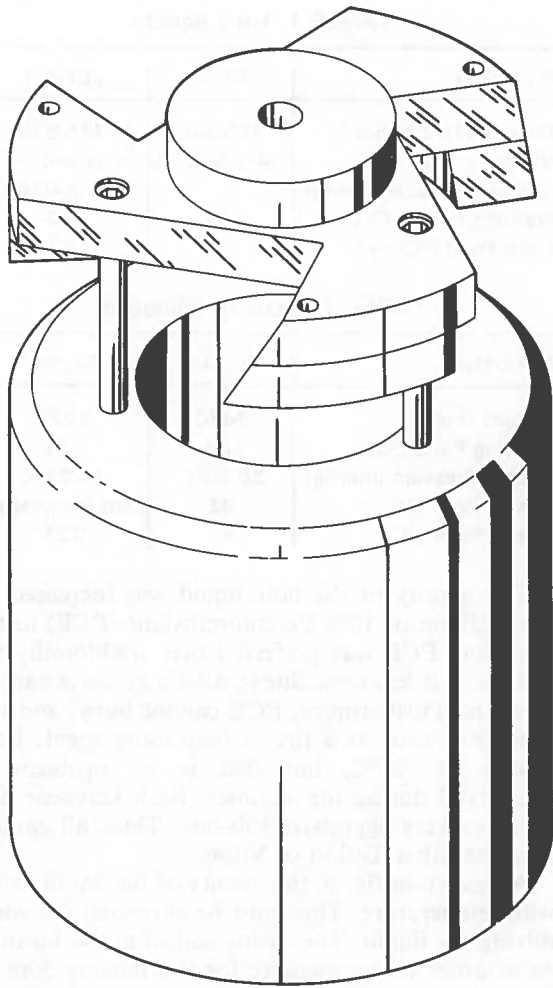


Figure 9. Reamer. The reamer is mounted on the exit shaft of the electronic section. The front cylinder centers the unit in the hole.

due to the missing 50 m of liquid. Although the change in hole diameter was small (Johnsen, 1980), any change could have stuck the drill. Therefore, the nominal diameter was increased from 129.5 mm to 130 mm before drilling resumed each season. A simple reamer (fig. 9) was used. It is mounted directly on the exit shaft of the electronic section. The front cylinder centers the reamer in the hole. During 1981, an improved version that could be bolted directly to the motor section was used.

Camp

The drilling took place inside a 24.4 m by 9.8 m shelter in a 18 by 6.7 m pit, 4 m below the original surface (fig. 10). This pit was connected by a tunnel to the science trench where numerous investigations were conducted continuously on the cores. Another tunnel connected the science trench and the core storage trench. A cold cave between the drill pit and science trench stored 40 m of core. Cores from the brittle zone (700-1400m) were stored 2 days prior to handling to reduce their fragility.

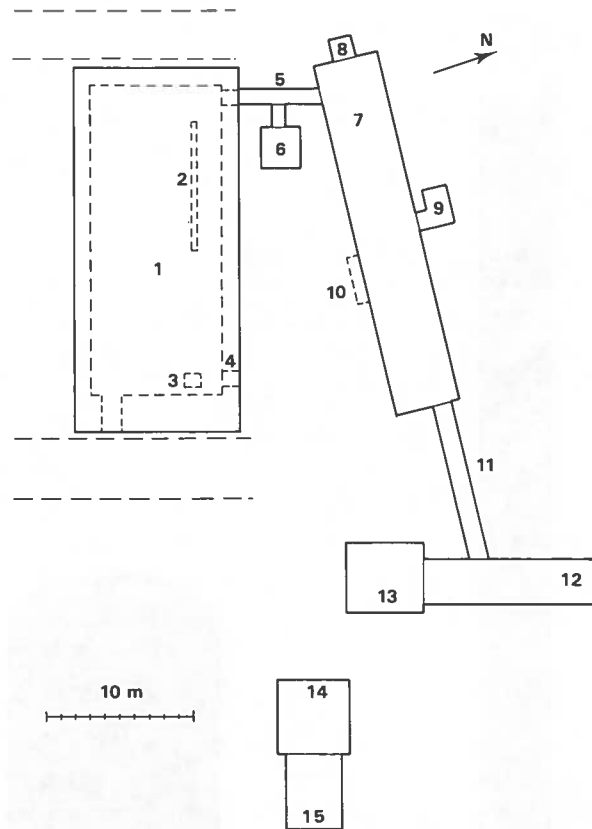


Figure 10. Dye-3 drill camp. The camp consists of the drill shelter, a science trench and a core storage trench. Tunnels connect the drill pit and the trenches. 1. drill pit, 2. 6 m deep pit, 3. winch, 4. pump station, 5. tunnel, 6. cold cave, 7. science trench, 8. emergency escape hatch, 9. surface conductivity cave, 10. dust room, 11. tunnel, 12. core storage trench, 13. weatherport entrance, 14. weatherport, 15. chemical lab-van.

A ventilation system with a capacity of 20,000 m³/h exchanged the air in the drill shelter 10 times per hour to reduce the presence of the toxic fumes from the hole liquid.

Results

The idea of making a new drill was first raised in the autumn of 1977. The basic principles of the drill were tested at Dye-3 in the summer of 1978, and the prototype was tested at CRREL in the spring of 1979 (Rand, 1980a). In 1979, a casing was installed by CRREL at Dye-3 (Rand, 1980b), and later the prototype drilled to 225 m. The core production was limited by weaknesses in the drill that were aggravated by rust particles from the casing. In 1980 the drill was improved, but a breakdown terminated the season at 901 m. In 1981, drilling started with run 755 and continued smoothly after the initial adjustments (fig. 11). The core production rate was 120m/week which is the same as for the Byrd Station drilling program. The termination of the

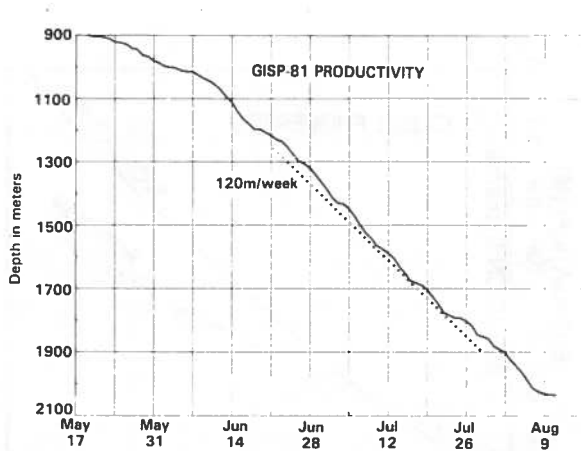


Figure 11. GISP 1981 production versus depth

last glaciation was found in run 1285 at a depth of 1786.80m. The first indication of bottom material was found in run 1371 at a depth of 1949.45 m. Silty ice started in run 1400 at 2012.83 m. The final depth was 2037.63 m in run 1418 when the drill was stuck. The drill was left with tension in the cable and excess pressure in the hole during winter. By the summer of 1982, the drill had become loose, and after being raised to the surface, the last core was removed from it. The drill itself was undamaged. 500 ml of the hole liquid had seeped into the pressure tight section.

The ice core by this drill is of excellent quality, and no part of the core is known to be missing. It is estimated that less than 2 m of core was lost, resulting in a core recovery of better than 99.9%. The brittle zone (the depth at which the core becomes brittle at the surface) was 700 m to 1400 m which compares with 400 m to 900 m at Byrd Station (Ueda, 1969).

The specific energy, that which is used to produce 1m^3 of cuttings, increased with depth in spite of improvements in the cutting system. Close to the hole bottom the specific energy was about 16 MJ/m^3 . This increase agrees with an estimated increase in fracture stress with pressure (Shoji, 1978). Ice from the ice age shows a marked reduction of viscosity (Shoji, private communication), however this does not change the specific energy.

A cable-suspended drill tends to deviate from the vertical as it penetrates. Fig. 12 shows the hole inclination with depth. At a depth of 1400 m, modifications to the cutters stabilized the inclination at 6 deg compared to 15 deg at the bottom of the Byrd Station borehole (Ueda, 1969). The azimuth is not known.

The ice temperature close to surface was -20°C , and at the bottom, the transducers inside the drill measured the temperature at -12°C in 1981. In 1982 the hole temperature close to the bottom was measured at -13.40°C using a calibrated thermistor. The reason for this change is not yet known.

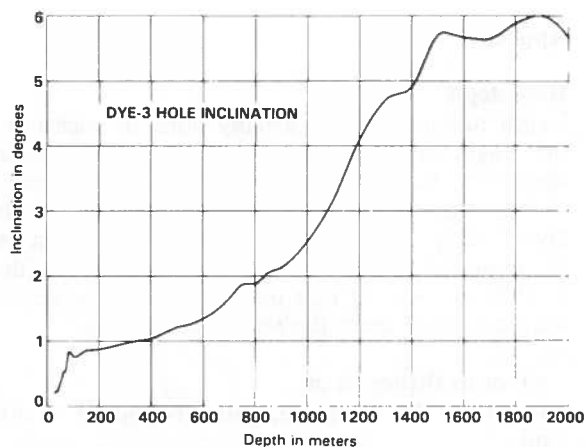


Figure 12. Inclination of the drill hole. Azimuth is not known.

Conclusion

A new deep ice core drill for cold ice has been developed. It has a demonstrated capability of drilling a 2 km ice core, and the same principles can be used to a depth of 3.3 km. The basic concept of the instrumented drill, i.e., the battery section, the replacement of mechanics with electronics, the in-principle simple mechanics, worked as anticipated. There is no indication that we are close to a limit of the system; a longer drill would be able to take longer cores thereby increasing the penetration rate, and the system could be made to work with minor modifications to the electronics, in very cold ice. The penetration rate is 120m/week. The drill is easy to maintain in the field. The ice core is continuous and of good quality. Due to the use of a microprocessor in the drill, an operator can be trained in just 3 days.

Acknowledgement

The drill head used in 1980 and 1981, and the reamer used in 1981 were manufactured at the Physics Institute, University of Bern by Mr. Henry Ruffli. Numerous colleagues from the universities of Bern and Copenhagen served as drill operators. The Polar Ice Coring Office, University of Nebraska-Lincoln provided logistic support, and the 109th TAG, New York Air National Guard and the Royal Danish Air Force provided air support. The Danish Arctic Contractors helped in Sondre Stromfjord, and the personnel at the Dye-3 radar station showed a great hospitality and patience. K.C. Kuivinen and H.B. Clausen reviewed the manuscript.

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Appendix

Hole depth

Depth measurement is usually done by measuring the length of the retrieved core. In a multiseason operation vertical strain makes the core length shorter than the actual depth of the hole. In the Dye-3 deep drilling, all depths are given as accumulated core length with reference to the June 8, 1979 surface. At that date, the following depths were measured from the reference surface:

- 4.0 m to shelter floor
- 10.5 m to top of casing, which is bottom of drill pit
- 68.5 m to top of thermodrilled hole inside casing
- 81.7 m to bottom of thermohole, start of ISTUK drilling.

The bottom of the casing was at 76 m (Rand 1980b). In 1980, the casing had moved 30 cm up relative to the bottom of the drill pit. This indicates, that the casing followed the ice movement of the 68 m layer where the casing was fixed to the ice by the frozen water. The 30 cm movement is in accordance with the difference in annual ice thickness of 92 and 60 cm at the depths of 10.5 and 68 m respectively. In order to ensure clearance, the upper 89 cm of the casing was removed in 1981. In 1982, PICO added 45 ft. of casing.

The amount of core retrieved was measured by placing the cores on high quality graph paper, and fitting the cores together. Due to deficiencies in this procedure in 1979, the actual hole length may be up to 65 cm more than indicated. In the following years, starting from a depth of 224 m, the procedure was improved.

Drill Cable

The manufacturer performed the following measurements prior to delivery:

1. Diameter measured under light tension every 300 m varies from 6.38 mm to 6.40 mm.
2. DC conductor resistance is $15.75\Omega/1000\text{m}$, all 4 conductors in parallel.
3. Capacitance is 148 pF/m, one conductor to all other and armor together.
4. Breaking strength: 28.5 kN, ends fixed, 23.6 kN with one end free to rotate.
5. Breakdown voltage with cable bent over 10 inch diameter sheave: 10 kVAC was applied between conductor and armor and no breakdown occurred.
6. Elongation and rotation, see fig. 13.

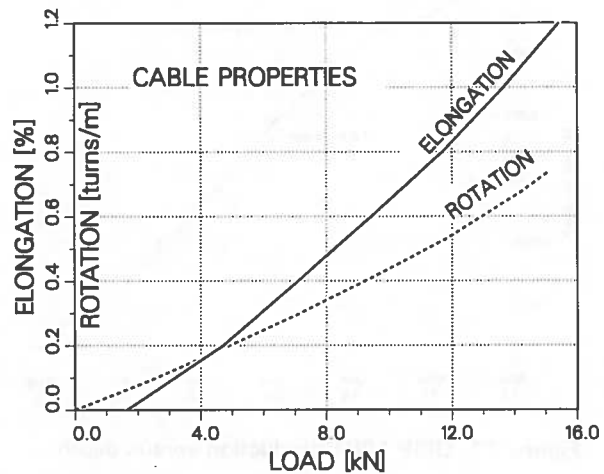


Figure 13. Cable elongation and rotation versus cable tension.

Drill communication

The drill computer measures the following parameters:

- 1 Cutter load measured as load on the cable
- 2 Loss of antitorque measured by differential inclinometers
- 3 Motor current
- 4 Inclinometer X
- 5 Inclinometer Y
- 6 Cable voltage at drill
- 7 Internal 89V supply
- 8 Motor voltage
- 9 Battery current
- 10 Battery common voltage
- 11 Motor common voltage
- 12 Inclinometer voltage reference
- 13 Leak detector, upper sealing
- 14 Internal 5V supply
- 15 Battery temperature 1
- 16 Battery temperature 2
- 17 Battery temperature 3
- 18 Motor power supply temperature
- 19 Motor temperature
- 20 Computer temperature
- 21 Pressure tube temperature
- 22 Upper power supply temperature
- 23 Battery voltage, all 5 strings, 55 cells
- 24 Battery voltage, 4 strings, 44 cells
- 25 Battery voltage, 3 strings, 33 cells
- 26 Battery voltage, 2 strings, 22 cells
- 27 Battery voltage, 1 string, 11 cells
- 28 Pressure in electronic section
- 29 Leak detector, motor shaft
- 30 Leak detector, lower sealing.

In addition screw length (motor rotations), digital status and error codes are transmitted to the surface. Cutter load, loss of antitorque, motor current, screw length and status codes are transmitted every second. The other channels are transmitted on a cyclic basis, providing a complete update every 6 seconds.

The drill is controlled from the surface by setting 7 bits of information: one is the motor ON/OFF switch, two controls the 4 possible motor speeds, one reverse the motor, two control the battery heaters and the last bit control the battery charging. Although the operator can control these bits directly, the normal control is at a higher level, f. ex. the operator can initiate the following sequence by a single keystroke:

Fast reverse rotation of the drill. When close to the end of the screw rotate reverse at minimum speed until end of screw. Then motor is switched OFF and screw length is reset.

This sequence is controlled by the drill computer.

Productivity

The time to drill a hole can be calculated knowing run length, winch speed, drilling- and surface time (Johnsen et al., 1980). The Dye-3 deep drilling was performed in 3 shifts, 24 hour a day, 7 days a week except for a weekly 16 hour break. Towards the end of the last season, at a depth of 2000 m, the average run length was 1.9 m including lost runs. Winch speed was limited to 0.6 m/s due to deficiencies in the winch. Based on these figures, and a drilling time of 5 min, an effective ground time of 43 min, including the Sunday break, hole filtering, regular maintenance etc. can be calculated. Using the above figures, and a cable speed of 0.8 m/s, the time to reach depth x can be calculated as

$$t = 0.034/1.9 * x + 14.5 * 10^{-6}/1.9 * x^2$$

x in meters, t in days.

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THE CANADIAN RUFLLI-RAND ELECTRO-MECHANICAL
CORE DRILL AND REAMING DEVICES

G. Holdsworth
National Hydrology Research Institute
Environment Canada
Calgary, Alberta

ABSTRACT

An electro-mechanical ice core drill of medium depth capability, was built in Ottawa in 1980. The design is based on principles established by Rufli *et. al.* (1976) and Rand (1976). New to the design however, is a geodesic dome structure which serves both as a structural unit to support the central fixed tower and to provide shelter for the drill crew. The whole unit can be packed in shipping crates weighing a total of 760 Kg, and by suitable dis-assembly, may be fitted into a Helio-Courier (STOL) aircraft in about five loads, including the generator.

The ice core is about 96-100 mm in diameter, depending on the cutter setting, and averages about 1 m in length.

The drum has 270 m of cable with a tensile strength of 4200 Kg. The deepest holes to date are 103 m, in ice at -29°C, (Mt. Logan, 5340 m altitude) and 202.4 m in ice at -51°C, (South Pole, 3100 m altitude).

Currently being constructed, is an electro-thermal drill unit which will connect directly into the electro-mechanical cable termination. This design, (Zotikov, 1979) is based on the Soviet ETB-3 drill. The diameter of this drill is compatible with the hole drilled by the mechanical drill and similar sized cores will be produced. An anti-freeze fluid would be used below the firn/ice transition.

INTRODUCTION

The principle of operating an electro-mechanical rotary coring drill

in ice was firmly established by the USA CRREL drilling engineers operating a modified Arutunoff electro-drill, first in Greenland and then in the Antarctic (Ueda and Garfield, 1969), under the general direction of B. Lyle Hansen. A subsequent requirement for rapid retrieval of clean 100 m cores with light weight equipment, led J. Rand (USA CRREL) and H. Rufli (University of Bern) in the early 1970's to simultaneously develop similar core drills based on the same mechanical principles as the Arutunoff electro-drill. The design embodies a drill frame suspended by an electro-mechanical cable, wound on a drum situated below a tower with a pulley mounted on top. Power for the winch and cable conductors is provided by a suitable portable electric generator. The drill frame consists of a cable termination, the drill motor, a speed reducing gear, a torque limiter (or clutch), an anti-torque device, and lastly the outer barrel. The removable core barrel rotates inside this outer barrel.

The Canadian version of this drill was built in 1980 and briefly field tested in the Yukon before being used to obtain 103 m of core from a site on Mt. Logan (5340 m). The major problems encountered were poor cutter design, inefficient and inconveniently arranged core breakers, an inadequate anti-torque system, and a generator break-down. These all contributed to poor over-all drilling rates, particularly below the firn/ice transition (F/I/T). Attention was paid to these problem areas before

the drilling operations were carried out at South Pole in 1981/82. Despite these remedial actions, trouble was still experienced with both the cutters and the anti-torque system. Solutions to some of these problems are suggested.

DRILL RIG AND CORE DRILL DESCRIPTION

The equipment consists of (1) a geodesic dome, which acts both as a structural unit to support the tower and as a shelter for the drill crew; (2) a main base plate, on which is mounted the winch system, the tower and the control panel; (3) the core drill unit (Fig. 1a - 1c). These are now discussed in turn:

(1) The geodesic dome is constructed of 100 pieces of 2.5 cm (1") ϕ aluminum tubing with flattened and individually grooved ends which fit into key-ways on a hub situated at each node of the structure. The tubes are fastened to the hubs by washers and a single stove bolt and nut. Specifications and details of its construction may be found in Holdsworth (1979). Over-all dome diameter is 4.88 m (16') and its height about 2.29 m (7.5'). It may easily be erected by two persons in about 1.5 hrs. A heavy duty white canvas canopy covers the outside of the dome frame. In the crest of the canopy is a zippered/velcro fastener opening for tower access. The top rim of the pulley rises about 2.9 m (9.5') above the top of the dome, or 5.2 m (17') above the bottom of the base plate, which rests on the snow. The tower, pulley and winch follow the design of Ruffli (1976).

(2) A 1.2 m (4') x 0.9 m (3') aluminum base plate frame supports the tower, the winch drum, the winch motor and gear reducer, and the control unit. The tower is made from two pieces of 16.83 cm (6.625") ϕ aluminum tube (wall thickness 0.34 cm or 0.134"), 224 cm (88") and 254 cm (100") long. They are joined by an aluminum collar situated at the top of the geodesic dome. The collar has four external lugs which facilitate the connection of four turnbuckle ties, which hook onto the top ring of the dome, thus enabling the tower to be plumbed vertically. Initial coarse verticalizing of the tower is achieved by shifting the dome relative to the base frame.

The cable drum is made from rolled aluminum and is capable of accommodating up to 500 m of 0.8 cm (0.3") ϕ cable. However, at the full drum width of 41 cm (16") between flanges, the present tower is not high enough to avoid spooling

problems near the edges without a level winder. A movable set of flanges has been installed to alleviate this problem and 350 m of cable can be accommodated at a flange spacing of 31 cm (12"). The drum is keyed to the output shaft of a Morse 35RW-B reduction gear box (40:1 ratio) driven by a 2 HP, DC motor via a V-belt which acts as a torque limiter to protect the motor. This motor, and the 1 HP version in the drill unit, are both controlled by Doerr SCR motor controllers set on the control panel. These units must be warmed by heating pads at ambient temperatures below about -15°C . The panel frame also contains an ammeter/volt meter set for each motor and the input power supply at 220 V AC, which is converted to 180 V DC for consumption by the motors.

A digital counter counts the revolutions of the cable sheave, the shaft of which is connected to a direction sensing multi-pole switch. A depth resolution of 4 cm is achieved in steps of 4 cm with an accuracy of 1 cm at each step.

(3) Lastly, the drill unit is fixed to the cable by a termination installed by the manufacturer (Rochester Corp. USA). The cable is steel armoured and carries seven 22 g conductors in the core. Power is conducted two sets of three wires and the seventh is used as an earth. The cable has a breaking strength of 40.9 KN (9200 lbs) and a minimum radius of curvature of 22 cm, which determined the sheave diameter. For normal operations, this cable is heavier than is necessary. It is useful, however, in the case of a badly stuck drill.

A U-bolt, mounted on top of the drill frame, accepts the clevice from the cable termination. A pivot bolt completes the connection. The electrical conductors are led to the motor through an Envirocon seven pin plug and bulk-head connector mounted and sealed on top of the frame. Mounted around the motor are three 0.52 cm (0.2") thick x 3.8 cm (1.5") x 93 cm (36.75") plate springs, which provide anti-torquing action.

The motor output shaft is connected to a gear reducer, which is connected to a torque limiter, the output shaft of which connects to the core barrel cap by a quick release pin. The core barrel (218 cm long) is a seamless stainless steel tube with stainless steel auger spirals welded to it. Three spirals with a pitch of 22 cm emanate from the three cutters set in the drill shoe. These spirals direct the cuttings to an inlet port at the top of the barrel.

The cuttings and the core must be separated within the core barrel to prevent the core from being impeded in its smooth upward motion relative to the core tube, during cutting and to prevent damage to the core during its extraction from the tube if it becomes jammed with chips. The separation is achieved by inserting a sliding disc inside the core barrel, a technique devised by H. Rufli. The remainder of the core barrel functioning is given in Rand (1976) and is evident from Fig. 1c. Further coverage is given in the next section.

SPECIFIC AREAS CONSIDERED CRUCIAL TO SUCCESSFUL DRILLING/CORING OPERATIONS

Cutters

For fast and consistent drilling rates, the three cutters must be efficiently designed according to the basic principles discussed by Mellor (1976,1977) and correctly matched. If they exist, deficiencies in design appear near the F/I/T. The cutters used are the oval type designed by J. Rand. For the Mount Logan operation, cutters with different back rake (30° , 35°) and clearance angle (15° , 20° , 25°) were tried. Some cutters were hardened, others unhardened, to allow filing for experimentation purposes. This practice should be avoided, since without a jig, sharpening was poorly executed in the field. It is clear that cutters should be of hardened steel or that they should have tungsten carbide inserts. The most efficient and stable clearance angle below the F/I/T was about 15° and the back rake about 30° to 35° . The clearance between the tips of the cutters and the rim of the shoe should be able to be controlled, as Johnsen *et al.* (1980) point out. Cutters with large clearance angles (20° - 25°), although satisfactory in firn, caused frequent anti-torque failures in ice. This, combined with progressive dulling of cutter edges (causing powder sized chips and subsequent packing in the lower spirals) contributed to the over all low drilling rates (Fig. 2). The cutters used at the South Pole were hardened drill rod steel, and again the optimum clearance angle was 15° with a 4 mm clearance. Some cutters were given a hollow ground back rake face, in order to reduce the back rake angle near the tip without compromising the overall strength of the cutters. This evidently caused excessive wear on the blades because of the small

included angle and because the edge temper of the steel was lowered by the grinding process. Beyond the F/I/T, the cutters had to be removed and resharpened, otherwise the cuttings would be fine powder instead of coarse chips. Repeat-sharpening also caused a reduction in the bottom clearance of the order of 0.5 mm. Coring runs were temporarily improved by sharpening after each run below 150 m depth. Subsequent checking of the hardness of the cutters revealed hardness irregularities over the surface. Hubs exceeded Rockwell 50 whereas blade areas were significantly less hard. Tests should be made before the cutters are installed. Tungsten carbide tips seem to be the answer to this problem.

Core Breakers

For good quality and efficient core breaks, proper attention must be paid to the design of the core breaker/catcher. For the South Pole operation, breakers were used that were designed by B. Koci of the Polar Ice Coring Office, Lincoln, Nebraska. In general, proper shape and blade length are needed to ensure a satisfactory fracture regime under moderate core break tension in the cable.

Initially, core breakers were only 1.3 cm (0.5") wide. This is insufficient for firn cores which tend to drop through the breakers upon lifting. For the South Pole operation, the width of the core breakers was increased to 1.9 cm (0.75"), thus increasing the circumferential coverage of blade edge to 18%. This ensured the retention of firn cores and seemed to give cleaner core breaks. Core break tensions in the Mt. Logan operation were estimated from winch motor current drain to be about 250 Kg whereas for the South Pole operation, many tensions were under 180 Kg, at a cable length of 100 m. These values include the weight of the drill and the suspended cable (about 90 Kg).

It is considered important to have hardened breakers in case a core site is exploited where fine particles, capable of causing wear on the edges, occur in the ice.

Anti-torque System

The use of plate springs to provide anti-torque against outer barrel rotation seems to be the simplest and most effective system. In the manufacture of the springs, insufficient attention was paid to the correct dimensions and tol-

erances. Hasps were slightly overthickened, causing a tight fit in the hole. This was serious near the F/I/T when a "stick-slip" type of movement developed. Above this, the firn was sufficiently deformable to allow downward motion of the springs. Also, two of the blades had a significant twist which reduced their edging effect particularly below the F/I/T. The addition of passive ice blades (or skates) on the springs (Fig. 3a) is of dubious value unless the leaf springs meet tolerances, and the ice blades have the correct rise. A solution not yet tried is to make the skates of spring steel so that the sharpened edges press against the bore hole wall (Fig. 3b). For optimum performance, the main plate springs should be shaped so that an even pressure distribution is exerted along their length (Johnsen *et. al.*, 1980). There should also be some simple method of simultaneously adjusting tension in all leaf springs. This is necessary when going from firn to ice.

The torque limiter was set at about 35 ft. lb. (0.14 m. Kg), but was apparently never activated. Detection of anti-torque failure was by monitoring cable twist. This practice should probably be avoided in favour of a lower setting on the torque limiter and an alarm system, or else by the use of slip rings on the cable (Rufli *et. al.*, 1976).

DISCUSSION OF CORE QUALITY

Generally, core quality for sampling purposes, was quite acceptable. Core breaks represent, over all, the single most disruptive feature of the core, although almost invariably, successive cores can be matched over part of their circumference. In the case of a very irregular break (possibly due to only one or two breakers operating) there will be slivers of core some of which fall back down the hole during winching up. From time to time, core is broken across, and this is seen to occur during drilling by a pulse in drill motor current. It is probably due to irregular drill feed rates. A recurring feature of core damage after the F/I/T is axial flaking of the sides of the core. It occurred below 80 m on Mt. Logan and below 150 m at South Pole. The exact reason for this is not known, but because the flakes appear to originate at the core breakers they may be caused by mechanical shock. Cutters were used which had a 2 mm (0.080") outside clear-

ance and a 1.5 mm (0.060") inside clearance. This does not represent efficient cutting, but the slightly over-sized hole produced combined with low pressure on the cutters for the first 30 m, probably contributed to the relatively straight holes drilled. Core diameter was typically between 96 mm and 98 mm depending on the cutter widths and the hardness of the ice.

FUTURE DEVELOPMENTS

An electro-thermal (E-T) corer is being constructed after the principles of the ETB-3 drill of Morev (Bogorodsky and Morev, 1984). The heaters used will be the units described by Koci (1984), which are able to operate on the same line power as the electro-mechanical (E-M) drill motor. As a result, it will be possible to operate both drills with the same drill rig, simply by disconnecting the E-M drill (used principally in the firn) and replacing it by the E-T drill (used below the F/I/T).

A wider range of winch speeds is desirable. At the low speed end, the motor controllers tend to cause irregular feed rates and some undesirable manual control has to be exerted. This may have contributed to unwanted cross breaks in the core. On the other hand, winching up rates are too slow, contributing to longer turn around times. A solution is to use two motors, one for each function.

DRILL ACCESSORIES

In order to utilize the bore hole for measurements that will provide information on ice deformation, and thus compliment the ice core research, two reamers were constructed. These are, first, a general bore hole reamer which scrapes the wall of the hole to counter closure if this is a significant factor, and second, a bore hole notch reamer, which cuts a notch or horizontal groove in the bore hole wall at selected intervals down hole. Both reamers are able to be attached to the output drive shaft of the E-M drill by means of a long connecting rod (Fig. 4) fitted with bearing wheels and a universal joint to eliminate any detrimental bending moment that could be generated during the reaming action.

The first reamer (Fig. 5, Right) has eight cutters that may be adjusted

to a given clearance. Cuttings fall into a reservoir rigidly attached below the reamer section, and separated from it by a neoprene annulus which prevents any chips falling into the bore hole.

The second reamer is shown in Fig. 5 (Right). Three semi-elliptical cutters are attached to the mid-points of three leaf springs which exert an outward pressure towards the wall of the bore hole, thus loading the cutters. The leaf spring pressure is adjusted by means of an axial compression spring. The cutting action is terminated when the leaf springs make contact with the bore hole wall, and the radial thrust of the springs is almost exhausted. This action can easily be monitored on the ammeter connected to the drill motor circuit. As before, cuttings collect in the detachable chip reservoir which can serve both reamers.

A bore hole logger has been designed to sense the notches in the bore hole wall. From successive bore hole surveys, the change in spacing between notches can be easily determined. This, in turn enables the bore hole parallel, or approximately, the vertical strain rate, to be computed. This strain rate is a valuable parameter to know in ice dynamics problems.

ACKNOWLEDGEMENTS

John Rand and Henry Rufli provided me with the full benefit of their combined experience with E-M core drill development, and the relative success of this operation was due largely to them. Most of the pre-machining design phase was ably accomplished by Duncan Watt of Carleton University, Ottawa, and the machining and assembly was done at the Mechanical Engineering Department machine shop under the direction of S. Rocque and J. Herler. The reamers and some modifications to the drill were made at the National Research Council Mechanical Engineering Workshop in Ottawa. Extensive testing of the 10 KW generator for high altitude operation on Mount Logan was also carried out at the NRC.

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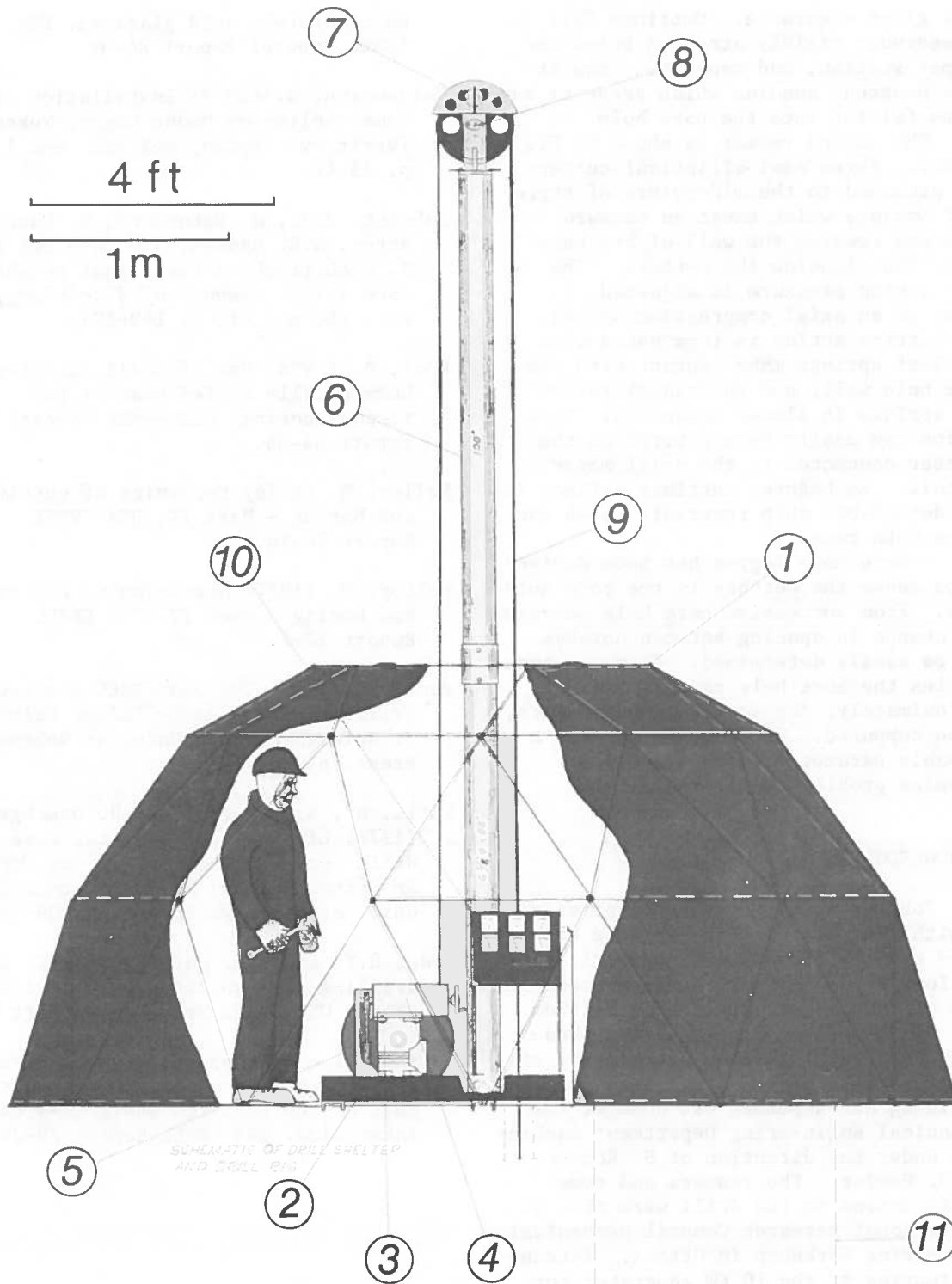


Figure 1a. Complete drill rig assembly (Drill unit not shown). (1) Tubular aluminum geodesic frame and canvas cover. (2) Base plate, of aluminum channel and ply-wood construction. (3) Gear reducer. (4) Winch motor. (5) Cable drum. (6) Aluminum tube tower in two sections. The drill unit is broken down into two parts which fit inside the tower sections for shipment. (7) Pulley cover, aluminum. (8) Revolution counter switch housing (not shown, but mounted on pulley support plate). (9) Electro-mechanical cable. (10) Power conversion unit and control panel. (11) Snow pit, approximately 4' x 3' x 4' (deep) (1.3m x 1m x 1.3m) necessary for extracting core barrel from the drill unit.

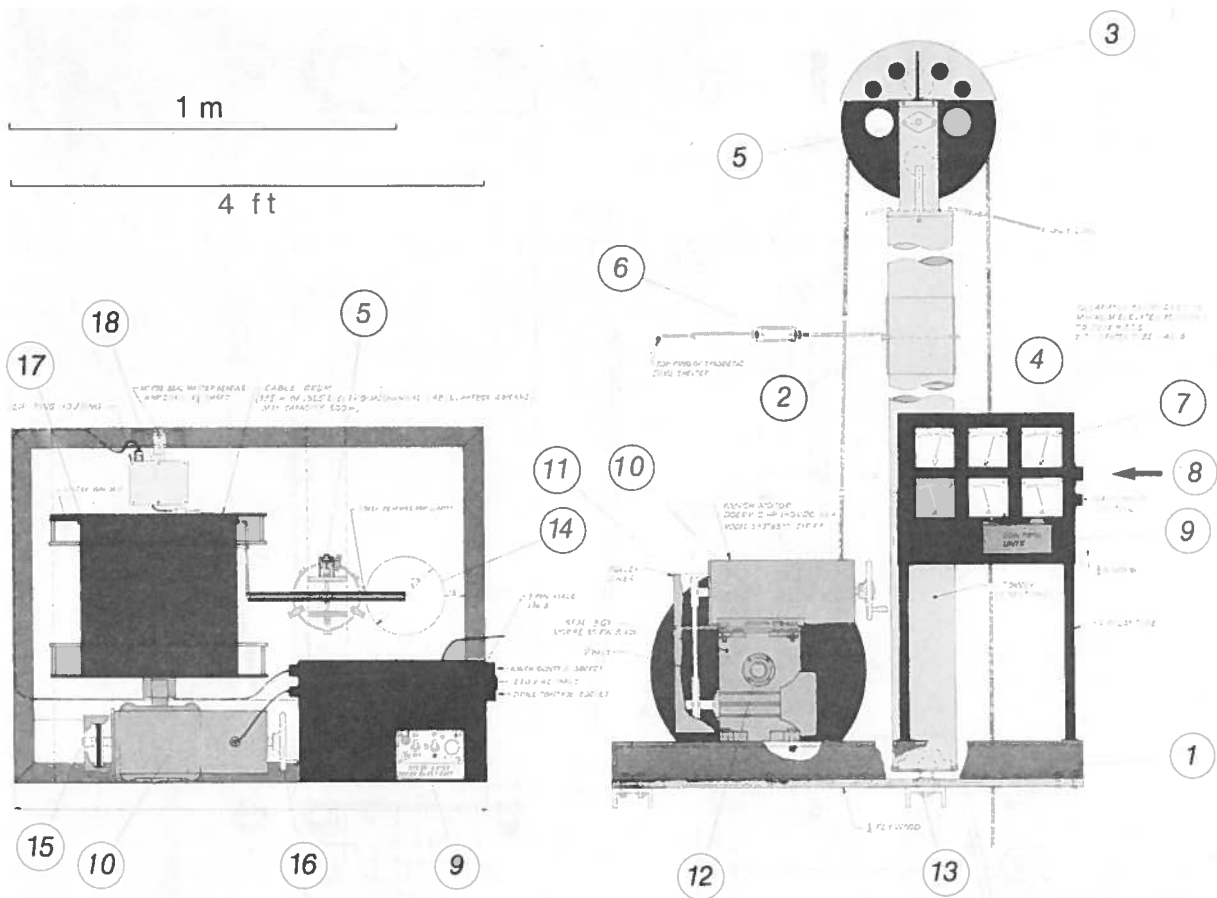


Figure 1b. Winch, tower and drive assembly. (1) Base plate, 4' x 3' (1.22m x 0.91m) constructed from aluminum channel with a ply-wood base containing a drill access hole. (2) Aluminum tube tower, 6.625" diam (16.83cm) in two sections joined by an aluminum collar fitted with four lugs at 60° and 120° which enable connection to the top ring of the geodesic dome for stability. Guy lines from the top of the tower are not necessary under normal conditions. (3) Pulley belt cover. (4) Electro mechanical cable (Rochester Corporation, number 7-H-325A, 0.313" (0.80cm) diam. 7 conductor. Length approximately 270 m. (5) Position for multi-pole switch for counting pulley wheel revolutions. Electrical conductor is fed through center of tower to digital counter on control panel. (6) Hook, rod and turn-buckle linkage to top ring of geodesic dome (four connections). (7) Power conversion unit and control panel with ammeter/voltmeter pair for input power, winch and drill motors. (8) Input power from generator (220 V AC at 3.5 KW). (9) Motor controller (Doerr Electric Corporation, Wisconsin). SCR solid state unit with forward, reverse and neutral or brake positions. Separate units are used for winch and drill motors. (10) Winch motor (Doerr Electric Corp.). Permanent magnet, 2 HP, 180 V DC, 11.6 A, 1750 RPM. (11) V-belt drive with safety cover. (12) Gear case. Unit is a Morse 35RW-B, 40:1 reduction. (13) Ball assembly for support of tower base socket. (14) Drill access hole in plywood base plate. (15) Crank for manual turning of motor output shaft fits here. (16) Manually operated control wheel for low feed rates on the winch. (17) Cable drum with adjustable flanges (currently contains 270 m of cable) . (18) Slip ring housing for transmission of power to the cable and drill motor. Complete drill, winch and tower/dome assembly fits into 8 transit cases (not including generator) for a total shipping weight of 760 Kg.

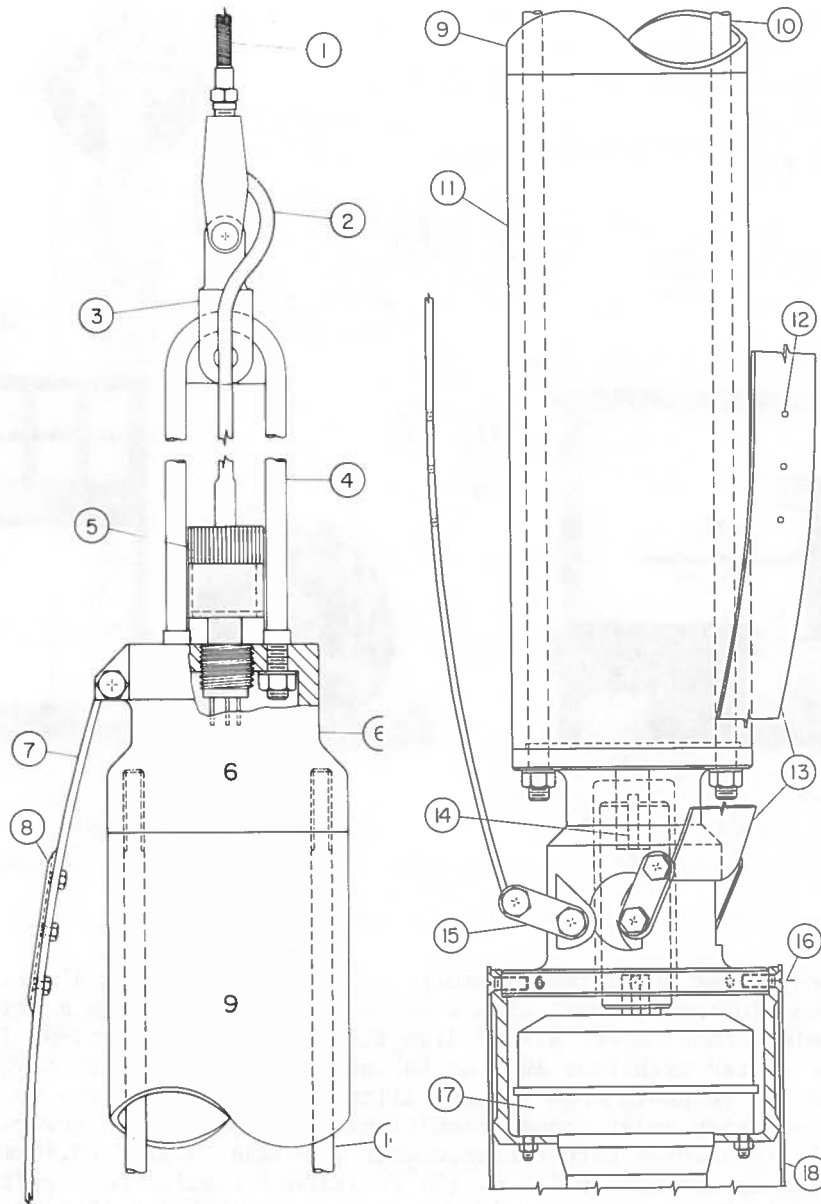


Figure 1c. Core drill unit. (1) Electro-mechanical cable (Rochester Corp. cable number 7-H-325A). (2) Electrical lead from cable termination. (3) Clevice connection to top of U-bolt on drill frame. (4) U-bolt. (5) Envirocon plug (VMK-FS) and bulkhead connector (VSK-7-BCL) assembly. (6) Aluminum end cap. (7) Plate spring (0.52 cm x 3.81 cm x 93.3 cm); three with fixed or adjustable hasps. (8) Ice blade attachment (see Fig. 3). (9) Extension tube (11.43 cm \varnothing x 47.3 cm). (10) Motor tie bolts. (11) Electric motor (Doerr Electric Corp., 1 HP, 1750 RPM, 180 V DC). (12) Holes for mounting ice blades. (13) Plate spring. (14) Keyed output shaft from motor, and gear box coupler. (15) Connecting link for spring attachment. (16) Screwed break point for drill dis-assembly. (17) Gear reducer (Sumitomo, cycloid drive, 17:1).

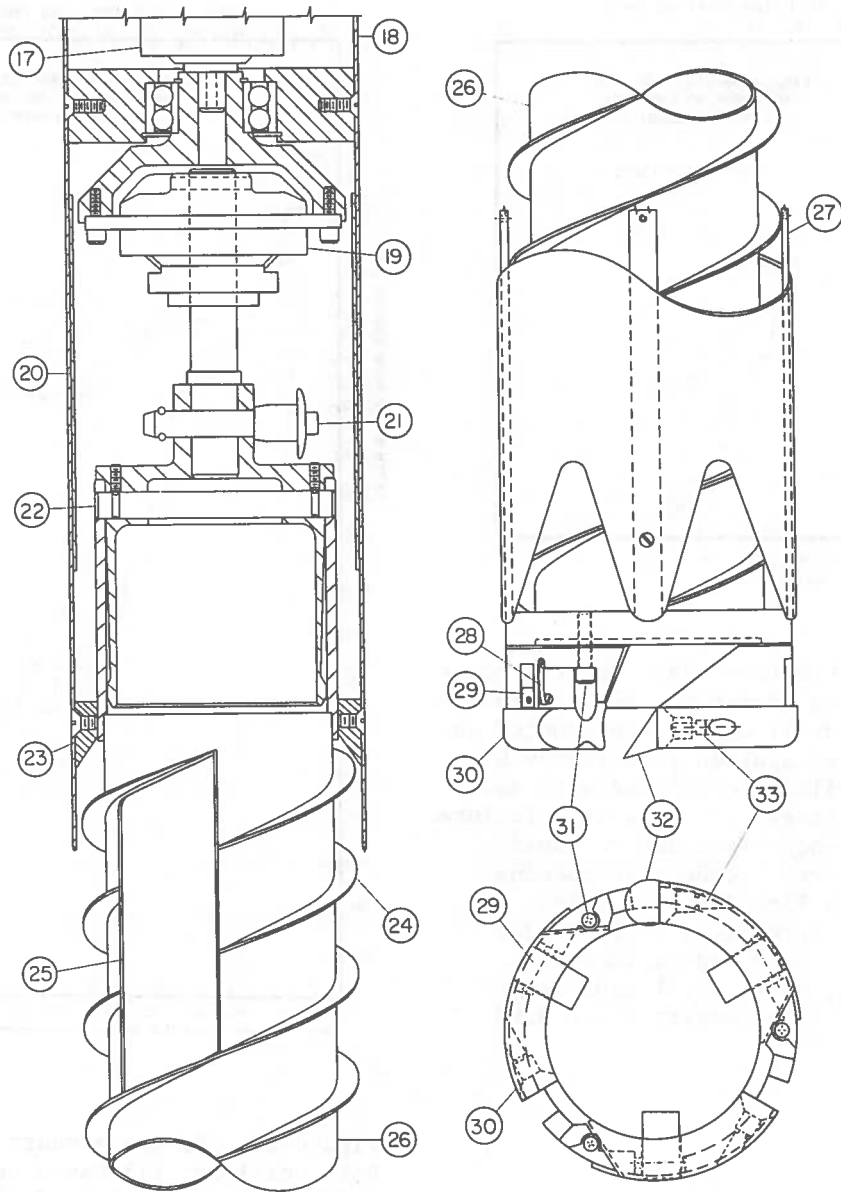


Figure 1c (continued). (18) Outer barrel (0.165 cm x 13.97 cm x 262.9 cm stainless steel). (19) Torque limiter (Morse 350A-1). (20) Rotary cover on release pin access hole. (21) Quick release pin. (22) Core barrel release pin. (23) Nylon bearing ring and chip seal. (24) Stainless steel spiral of 22 cm pitch. (25) Ice cuttings inlet port. (26) Core barrel (0.165 cm x 10.8 cm x 218.1 cm type 304 stainless steel). (27) Core cuttings elevator strips and spiral bearing surface (brass, screwed to outer barrel). (28) Core breaker spring. (29) Core breaker (1.9 cm x 3.2 cm). (30) Shoe for mounting cutters and core breakers. (31) Cap screw attachment of shoe onto core barrel flange. (32) Oval type cutters. (33) Cap screw attachment of cutter into shoe.

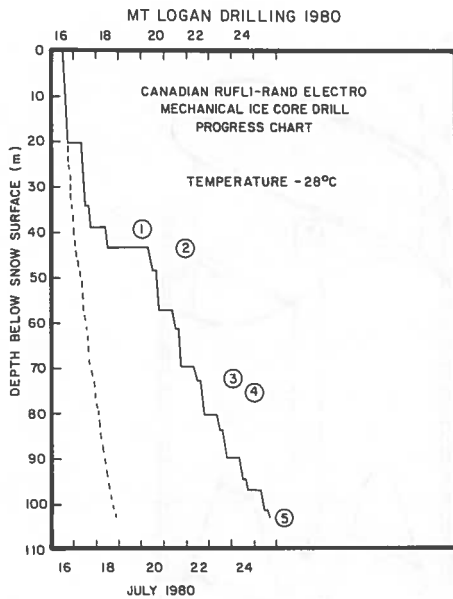


Figure 2a. Progress chart for the Mount Logan drilling operation. (1) Accumulation of fine drill cuttings prevented an advance. Water applied to solidify base of hole. Drilling continued with new sharpened cutters. (2) Generator failure. (3) Poor advance rates due to rapidly dulling cutters. Frequent sharpening required. (4) Firn/ice transition. (5) Drilling terminated at 103 m due to poor advance rates and expired time. In principle, drill still capable of taking core. Ice density above 0.90 Mg m^{-3} .

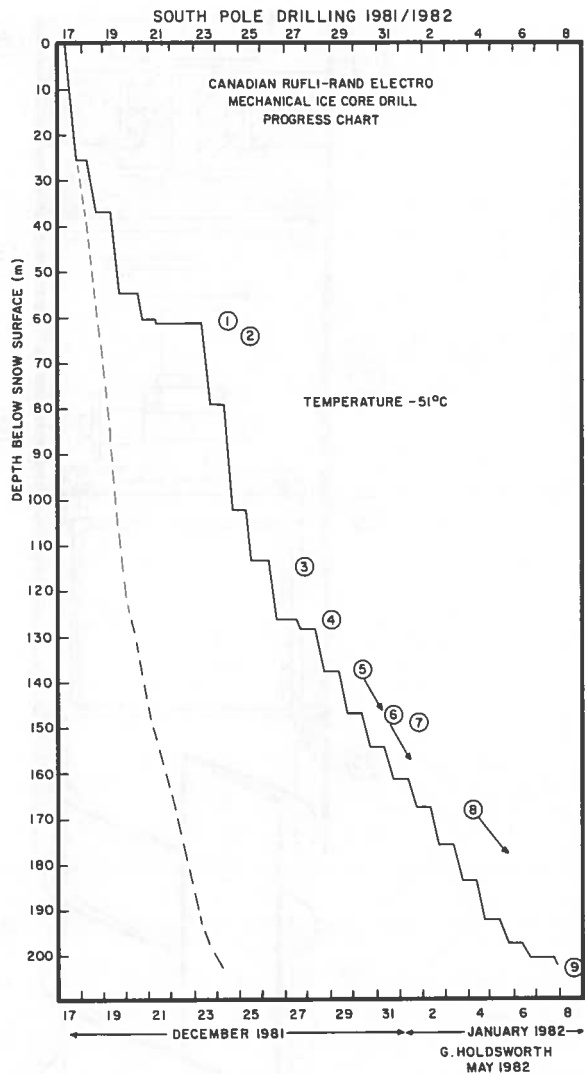


Figure 2b. Progress chart for the South Pole drilling. (1) Cable damage due to undetected anti-torque failure. (2) Anti-torque system retuned. (3) Firn/ice transition. (4) Fine tuning of the anti-torque system. (5) Cutters re-sharpened at regular intervals. (6) Beginning of sporadic longitudinal flaking of the core. (7) and (8) Cutters sharpened before each drill run and cutter sets rotated. (9) Hole terminated at 202.4 m, ice density $0.90 - 0.91 \text{ Mg m}^{-3}$. Drill still capable of penetrating further.

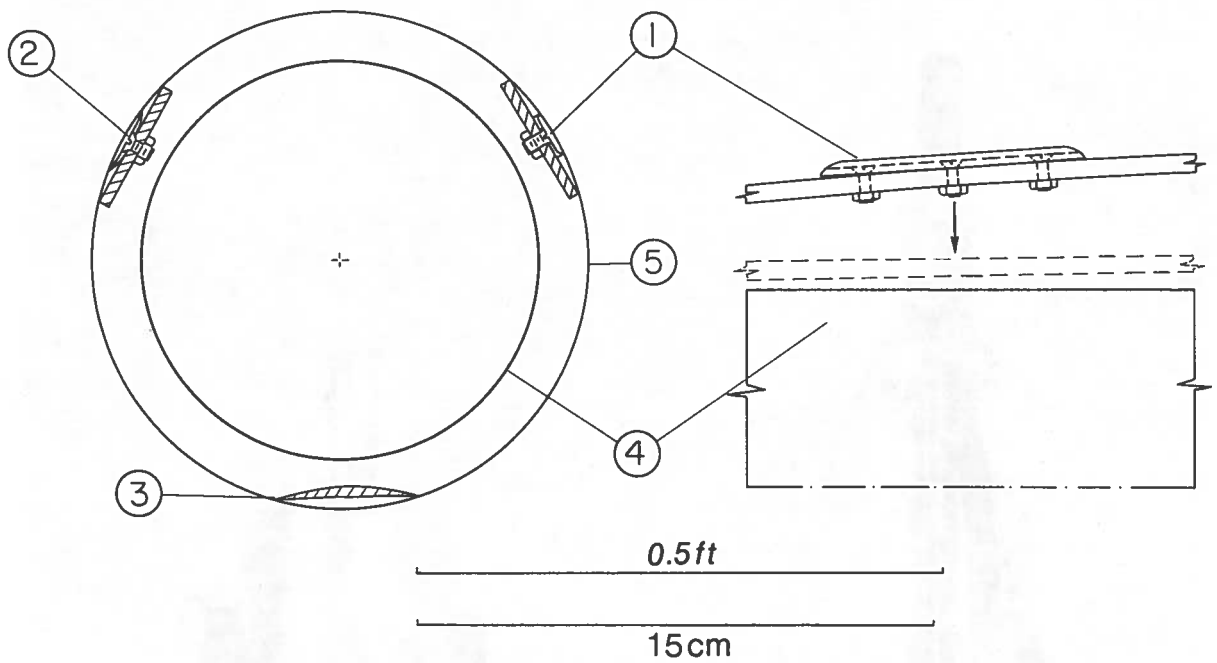


Figure 3. Ice blade attachments to anti-torque plate springs. (1) Passive blade. (2) Active blade (spring steel). (3) Alternate plate spring shape. (4) Motor casing or extension tube (5) Bore hole wall.

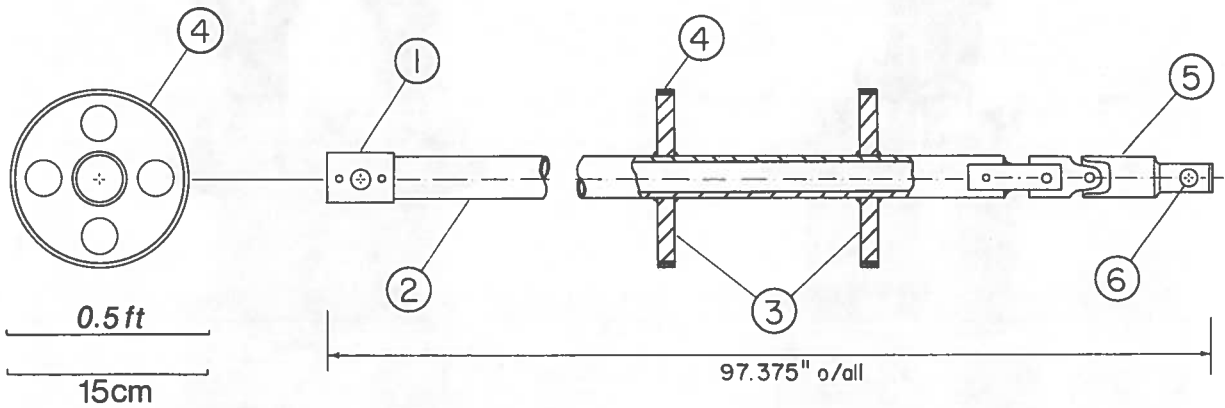


Figure 4. Connecting rod for reamer attachment. (1) Connection to clutch output shaft (see Fig. 1c item no. 21). (2) Main shaft. (3) Bearing wheels. (4) Teflon surface. (5) Universal coupling. (6) Connection to reamers.

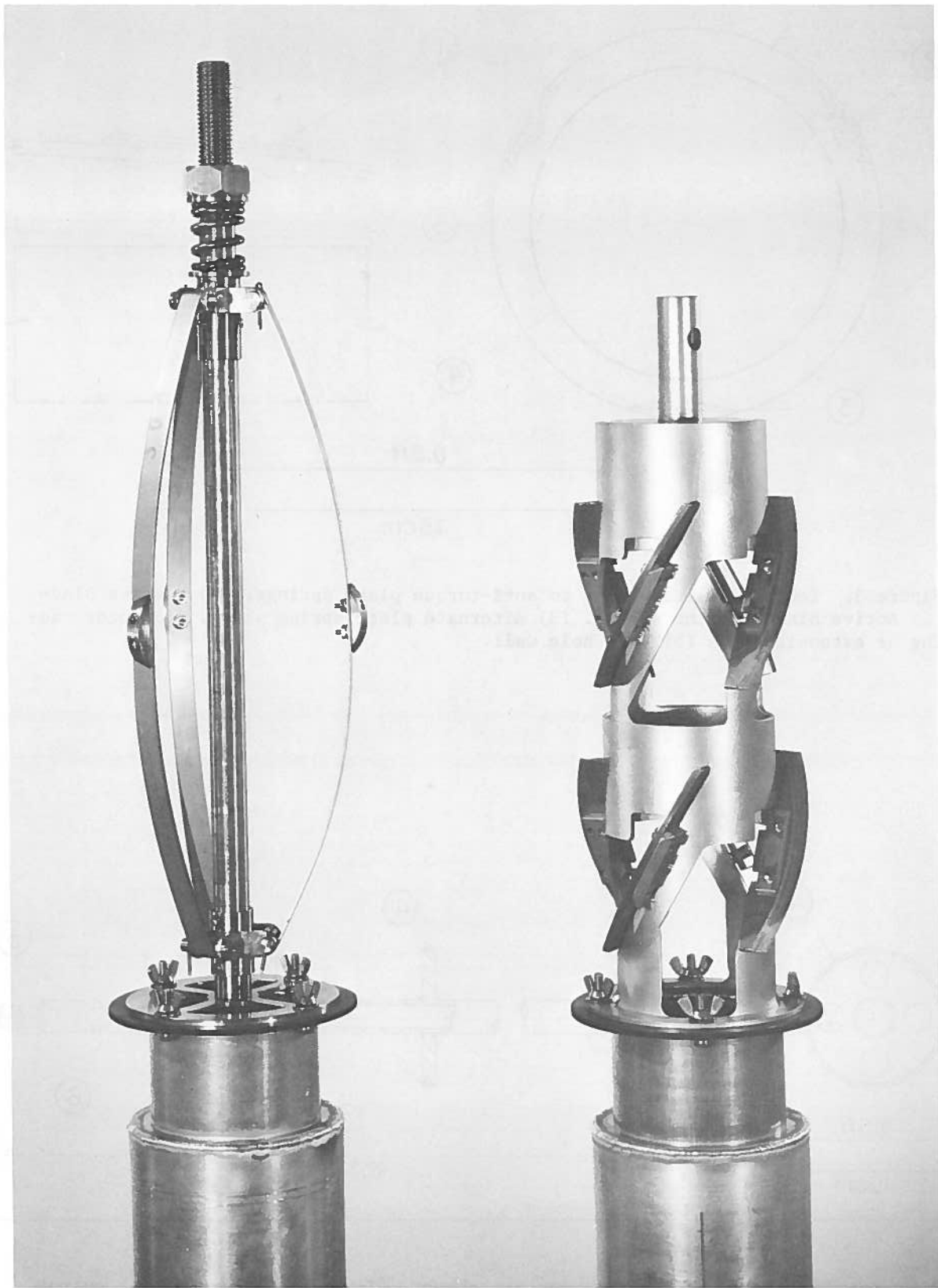


Figure 5. Bore hole reamers. (1) General bore hole reamer Mark I (right). (2) Bore hole notch reamer (left). Diameter of chip reservoir is 4 inches (10.2 cm), length 40 inches (100 cm). (Photo courtesy of National Research Council, Ottawa).

LIGHT WEIGHT ELECTRO-MECHANICAL DRILLS

Yosio Suzuki Institute of Low Temperature Science,
Hokkaido University, Sapporo, Japan

ABSTRACT

The ILTS-130 series, light weight electro-mechanical core drills, have been operated in various locations. Some are as short as 1.4 m and as light as 20 kg, yet capable of taking a 0.4 m length ice core in one minute, with a power input of 400 W. They are suitable for drilling to 30 m depth.

An extended version, 2.4 m in length and 28 kg in weight, took a 1 m length ice core in 2 minutes, during a laboratory test. This drill will be used in 1983 in Antarctica to replace the JARE-MID-140B drill, which, in 1980, cored a 100 m hole in 44 h and another 143 m hole in 81 h.

The basic design of the ILTS-130 series is described. Suggestions for further improvement and comments on planning a drill system are also included in the paper.

INTRODUCTION

For a drilling operation to be carried out by a small party with limited logistics, an electro-mechanical drill is superior to a thermal drill, because the former consumes much less energy than the latter. Several pioneering drills such as the Icelandic drill (Árnason, *et. al.*, 1974), the USA CRREL drill (Rand, 1976) and the Swiss drill (Rufli, *et. al.*, 1976) have established the basic design of the small electro-mechanical drill.

The Japanese Antarctic Research Expedition (JARE) had a requirement for

a drill system to core a 150 m hole. For this, the basic electro-mechanical drill unit was selected.

Although the first drill unit only reached 64 m (Ikami, *et. al.*, 1980), the second system was successfully used by JARE-21 to core a 100 m hole in 44 h and another 143 m hole in 81 h in 1980 (Suzuki and Shiraishi, 1982).

The second drill system consists of the following components: the core drill (JARE-MID-140B; 65 kg), a winch with a 150 m armored cable (W-9-150) (195 kg), a 2.8 kW generator (70 kg) and a controller unit (20 kg). The winch and the generator are mounted on a sled towed by an over-snow vehicle. The complete system may be set up and operated by 3 persons.

In the course of developing the two systems, a short test drill, 1.6 m in length and 30 kg in weight (ILTS-140B) was made. Slightly modified, it was later used in Antarctica to bore holes down to 30 m. The drill was suspended by either a manual or an electric winch and tower system with steel wire, while power was fed through an independent power cable via a controller from a 1.2 kW generator (35 kg). The total weight of the system, including a tripod, was less than 100 kg.

The ILTS-130 series, light weight drills were designed when the Water Research Institute of Nagoya University required a drill to be used on the Himalayan glaciers. Primarily intended for use in high mountains, they are

short and light. Of the four drills (ILTS-130A,B,C and D) equipped with the Mk I (1 m) barrel, model D is only 1.4 m long and weighs 19.8 kg. Combined with a commercially available light winch (300 Watts, 4 mm ϕ x 30 m cable), a 650 W generator, a tripod and a 30 m electrical cable, it is a light weight system, that may be back packed by three people.

Various field tests have proven the practicability of the drills. Model A has been used on a Himalayan Glacier, where a depth of 33 m was reached. Model B was used at Halley Bay, where a depth of 22 m was reached. Model C was used to core to a depth of 22 m in silty ground ice at Tuktoyaktuk, N.W.T.

These drills transported chips so easily, that an improved 2 m long barrel and corresponding jacket was fabricated. This Mk II barrel was laboratory tested. It took a 1 m core in under 2 minutes.

A fifth drill, ILTS-130E, will be equipped either with the Mk II barrel, or a Mk III to be made. This unit, with the W-9-150 winch, will be used in the Antarctic in 1983.

A 200 m drill system weighing less than 100 kg will be made for use in Antarctica in 1984.

The ILTS-130 series drills have the same basic structure, consisting of the drive unit, the barrel and jacket. They are derived from the earlier drills already described by Suzuki and Shiraishi, (1982). Table 1 summarizes the specifications of the different drill series.

DRILL STRUCTURE

Drive Unit

The center piece of the drive unit is the main shaft housing, which also houses the side cutter assembly. The jacket is fixed to the housing, while the barrel is connected to the lower end of the main shaft by an adapter. The power unit is mounted directly onto the housing, except in the MID-140B, which has an independent base for its power unit. The shaft is capable of sliding 30 mm relative to the housing, thus allowing the power section to hammer the housing when breaking core, in a similar way to the Danish drill (Johnsen *et. al.*, 1980).

Side Cutters

An electro-mechanical drill must counter the torque exerted by the action

of its cutters. Two anti-torque devices were proposed: the side drills and the side cutters (Suzuki, 1978). Tests showed the former to be impractical, but the latter to be very effective. This device was then installed in all later drills.

As shown in Fig. 1, three 45° spiral gears, transfer the main rotation to two horizontal axes of the side cutters, to make four grooves on the hole wall.

The guide fins placed in alignment with the side cutters, fit the grooves with a bottom clearance of 1 mm and a side clearance of 0.25 mm. The guide fins help the side cutters counter the torque. Some typical dimensions of the grooves are shown in Fig. 1. The cross-sectional area of the grooves is only a few percent of the main annular area. The short (10 cm long) guide fins of the ID-140 failed once in the JARE-20 operation when both the guide fins and the cutters were in a very weak depth-hoar layer. The guide fins lost alignment with the grooves and the drill became stuck. As a result of this, the fins were lengthened on later drills. In addition, the MID-140B was equipped with free-wheeling safety cutters behind its guide fins. These would cut new grooves for escape when a mis-aligned drill was pulled up. However, with its long fins, the MID-140B never mis-aligned in the JARE-21 operation, so for simplicity, the safety cutters were eliminated on the ILTS-130 series drill. The guide fins improve the straightness of the hole, while the side cutters either increase (by the use of the left-handed gears, as shown in Fig. 1) or decrease (by the use of the right-handed gears), the thrust on the barrel. For the ILTS-130 series drills the left-handed gears are appropriate.

Quick Barrel Releaser

The MID-140B and the ILTS-130 series drills were equipped with a quick barrel releasing mechanism (in the same manner as the Swiss drill) to allow barrel release irrespective of barrel orientation. A release ring, which can slide over the main shaft, is linked to a release shaft inside a center hole of the main shaft by a pin, through slits on the main shaft. The release shaft, in turn, is linked to joint pins in the connecting plug through a pantograph mechanism. A spring inside the main shaft pushes the release ring to its lower position, so that the joint pins pro-

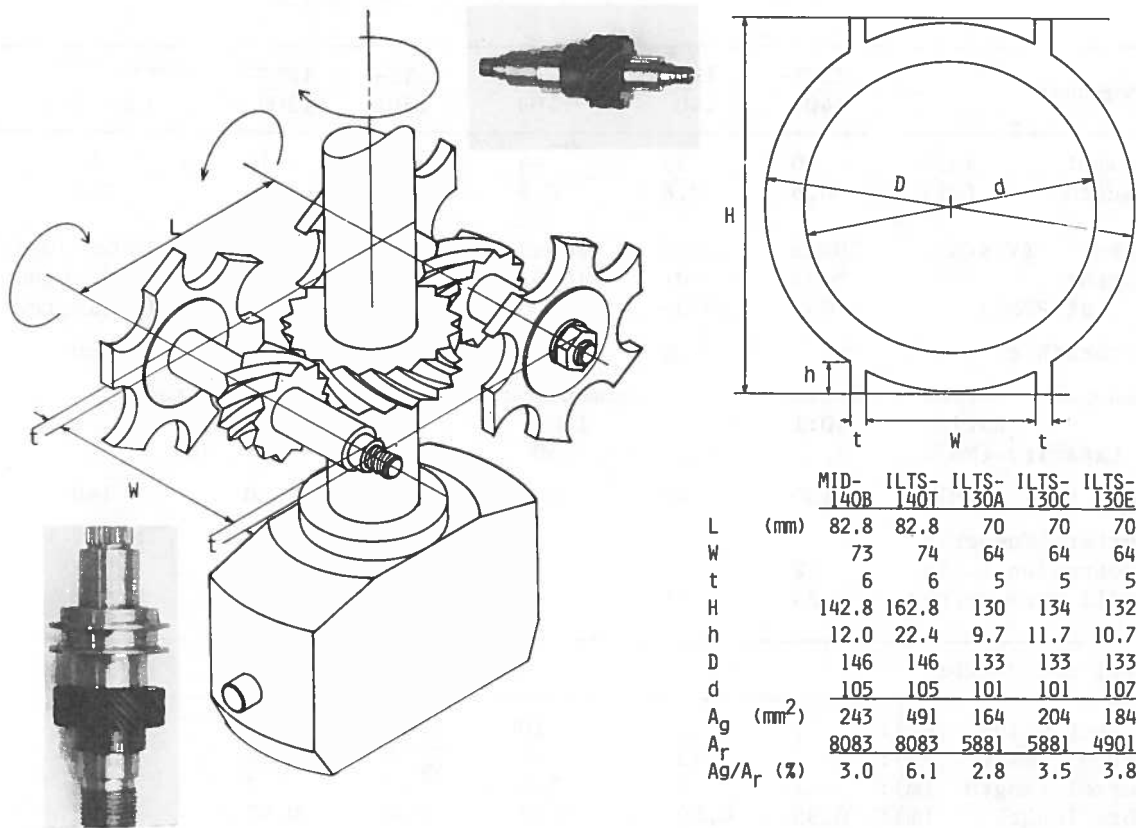


Figure 1. Drive mechanism for side cutters and the cross-section of the hole for the different drill series. A_g and A_r are the areas of the grooves and the annulus.

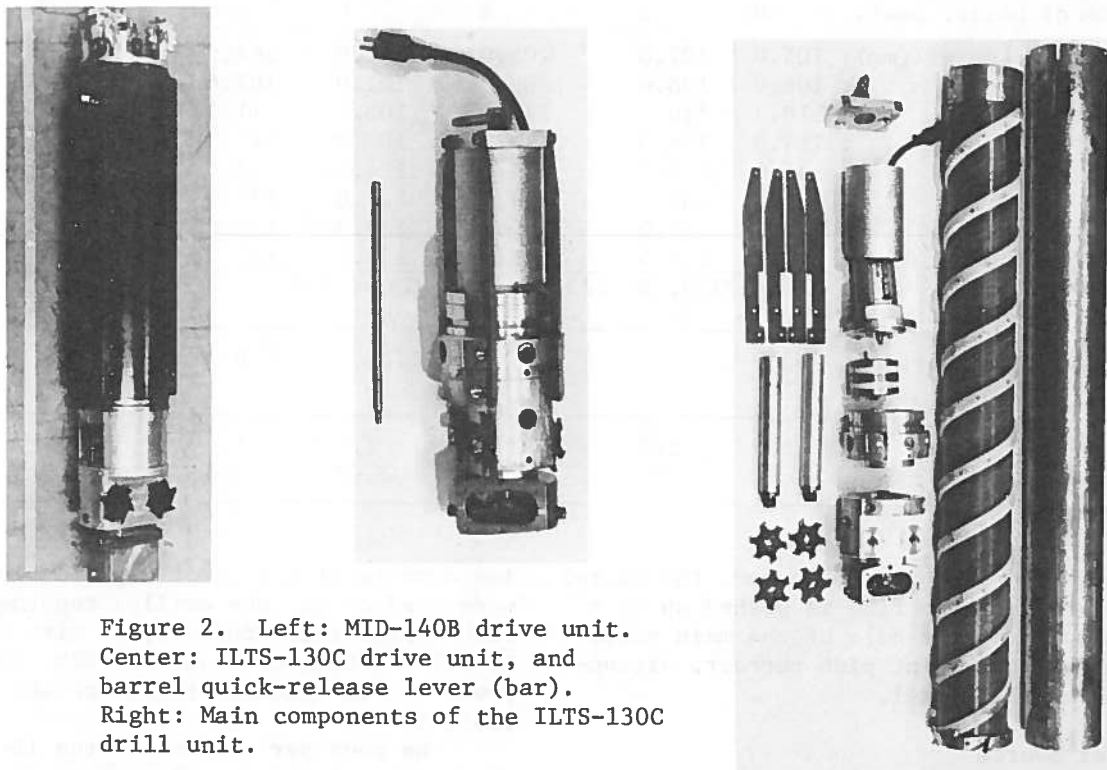


Figure 2. Left: MID-140B drive unit. Center: ILTS-130C drive unit, and barrel quick-release lever (bar). Right: Main components of the ILTS-130C drill unit.

Table 1. Specification of the drills

Drive-unit	ILTS- 140T	ID- 140	MID- 140B	ILTS- 130A	ILTS- 130B	ILTS- 130C/D,E
Weight (kg):	20	55	44	19	10	9
Length (m):	0.6	0.8	0.8	0.5	0.5	0.4
Input (V)x(A):	100x9	200x4	200x9	200x9	100x4	100x6/200x3
Output (W/ at RPM):	500/ 4000	450/ 10000	1000/ 10000	450/ 10000	220/ 15000	350/20000 (estimated)
Reversible?	no	yes	yes	no	no	no
Reducer Type:	Cyclo	Harmonic drive		Planetary		
Ratio:	40:1	100:1		5x5x5:1		
Capacity (Nm):	n.a.	50		30		
Main rotn. (RPM):	100	100	100	100	120	160
Cutters(Number):	2	2	2	4	4	4
Protrusion (mm):	2	4	4	2	0.9	0.9
Drill rate (m/h):	24	48	48	48	26	36
Barrel and Jacket				Mk I A/B/C/D	MK II	MK III
Jacket weight (kg):	7	12	10	4/6/4/5	10	10
Barrel weight (kg):	7	13	11	7/7/7/6	10	4
Barrel length (m):	1	2	1.5	1	2	2
Core length (m):	0.35	0.80	0.52	0.40	0.92	0.96
Auger slope (°):	25	30	25	30	40	45
Number of augers :	2	2	2	2	2	2
No. of vert. pawls :	2	2	2	4	4	4
No. of horiz. pawls:	0	2	2	0	0	0
Core diameter (mm):	105.0	107.0	105.0	101.0	107.0	109.0
Holder I.D. :	106.0	108.0	106.0	102.0	107.6	109.7
Barrel I.D. :	110.3	110.1	110.1	105.0	111.1	113.0
O.D. :	114.3	114.3	114.3	109.0	114.3	116.0
Jacket I.D. :	135.8	131.0	136.6	124.6*	123.8	123.8
O.D. :	139.8	135.0	139.8	127.0	127.0	127.0
Holder O.D. :	142.0	137.0	140.0	129.0**	130.0	130.0
Hole diameter :	146.0	140.0	146.0	133.0	133.0	133.0
*B: 123.0, D: 123.8				** C, D: 130.0		
Overall dimension				A(B)	C,D	E with Mk II (III)
Length (m):	1.6	2.8	2.3	1.5	1.4	2.4
Weight (kg):	34	80	65	30(23)	20	29(23)

trude from the plug to connect the barrel. When the release ring is pushed up by a lever, through a hole of the main shaft housing, the joint pins retract, disconnecting the barrel.

Power Source

Because of their light weight, ser-

ies commutator motors of high revolution were used on all the drills, together with a high ratio reducer, to give a barrel rotation of about 100 RPM. The power source specifications are shown in Table 1.

The poor performance of the ID-140, due to its very poor chip transportation was wrongly interpreted as being due to

the weakness of its 450 W motor. The MID-140B was then equipped with a 1 kW motor. However, the reducer (CS-25-100-GSPS, manufactured by Harmonic Drive Systems, K.K.) with a maximum output torque of 50 Nm, was unchanged, because no stronger reducer of the right size was available. The reducer was broken twice in the JARE-21 operation. The motor activated the horizontal pawls (described later) and the allowable torque on the reducer was exceeded. In drilling normally, a power of 450 W is adequate, so the 450 W motor was reused for the ILTS-130A unit without horizontal pawls. Motor power was further reduced on the later drills because they produced lower drilling rates, which gave improved core quality. Three 5:1 planetary reducer components (LUG-75-5MAD, -5MLD and -5MLG8: made by Matex K.K.) were used to get a final ratio of 125:1 at an output torque of 30 Nm. The combined dimension of the three components and the three spacers is a height of 53.2 mm. The diameter is 75 mm and the weight 923 g. A single 128:1 harmonic component (CS-20-128), with the same output torque, is 70 mm in diameter, 45 mm in height and 400 g in weight. Though a little bulkier and heavier, the planetary reducer was chosen because of its high efficiency (90 % in three stages, against 70 % for the harmonic reducer) and its ease of coupling to the input axle with a D-shaped shaft end and to the output axle with a serrated end.

Because of its small diameter (80 mm OD) and weight (1.2 kg) and easy availability, a motor taken from a disc grinder (PDA-100B; made by Hitachi Koki, K.K.) is now used on the ILTS drills. The motors are rated at 600 W at 100 V or 200 V. Its rotation is so high, that the main shaft rotation of the ILTS-130C with the 100 V motor, reached 160 RPM at 70 V, without the barrel and 145 RPM at 90 V when drilling in ice. The input current was about 4.5 A. It is recommended that the current be kept below 70 % of the rated value.

In order to activate the horizontal pawls, the JARE drill motors can be reversed by surface control. The ILTS-130 drills have no such function.

Jacket and core barrel

Clearances. The chip transport ability of a drill seems to depend strongly on (1) the clearance between the jacket and the core barrel (the barrel clearance) and (2) the clearance between the hole and the core (the cutter width).

The clearance between the core and the inner barrel (the core clearance) and that between the jacket and the hole (the hole clearance) must be sufficient to ensure smooth entrance of core into barrel and jacket into hole, respectively. Their values may be calculated from Table 1.

The barrel clearance and the cutter width on the ILTS-140T were chosen as near to those of the USA CRREL drill as possible: 10.75 mm and 20.5 mm respectively, while the core clearance and the hole clearance of the former are 2.6 mm and 3.1 mm respectively, both larger than the CRREL drill.

In order to decrease the cutting torque, the barrel clearance was reduced to about 7.4 mm on the ILTS-130 A to D drills (Mk I barrel and jacket). Since the chips were still easily transported, a further reduction of the barrel clearance is being tried on the ILTS-130E: to 4.75 mm in the Mk II and to 3.9 mm in the Mk III barrel and jacket. In laboratory tests, the Mk II easily transported chips along its 2 m length for cold ice but some problems exist if the ice is wet.

For the ILTS-130 drills, a core clearance of 2 mm is sufficient, but the hole clearance must be at least 3 mm for a jacket of seamed steel that has not undergone special shaping treatment.

Jacket. The two important roles of the jacket are to reduce the torque exchange between the barrel and the hole wall, and to secure smooth transport of chips. For the first role, the jacket should cover the core barrel as completely as possible. The jacket of the ID-140 had a few deep notches at its base, as they had been considered necessary for preventing chips from packing there, and straying into the hole clearance. Such prevention is a prerequisite condition for the second role. As the tests with the ILTS-140T drills showed the notches to be unnecessary, the later jackets are straight ended. The length of the ILTS-130 jackets is such that its base is about 3 cm above the upper surface of the cutter shoe. The distance of 3 cm, or ten times the hole clearance, seems necessary to prevent chips from straying into the hole clearance.

For chips travelling into the barrel clearance to be transported upwards by the auger flights, the jacket should prevent their rotation. For this purpose, either ribs were attached to the inner jacket wall (as on the CRREL and Swiss

drills) or grooves were cut on the inner wall (as on the Danish drill). Three steel ribs were welded onto the inner wall of the MID-140B jacket, resulting in large distortions of the jacket, which had to be straightened. On the Mk I and the Mk II jackets, aluminum strips, 10 mm wide and 0.3 mm thick were fixed with 0.5 mm thick adhesive tape, making the ribs of finished thickness 0.7 mm. From three to six strips were installed. The tape, a type used in carpet joining, was found to withstand water and temperatures as low as -40°C . On the Mk III jacket, with a tube clearance of only 3.9 mm, strips will be replaced by grooves.

Core barrel. The cutter shoe is attached to the lower end of the barrel. This assembly for the ILTS-130C and the MID-140B is shown in Fig. 3. The latter cutter shoe assembly would occasionally jam in ice, produce bad core quality and fail to break or hold core (Suzuki and Shiraishi, 1982). Anti-torque failure was attributed to sticking of chips

at the base of the shoe. Its shape was therefore changed in order to have a lower diameter at the base of the shoe. The horizontal pawls were abandoned because of their ineffectiveness. In comparison, the available force for activating vertical core breakers is about 30 times more. The much improved ILTS-130 shoe has four cutters and four core breakers. The latter successfully broke core at forces less than 2000 N. However, for holding firn cores, longer pawls of modified shape are needed. These have been fitted on the ILTS-130E shoe.

Only two auger flights are used, even with the four cutters. No difficulties were encountered with this arrangement. On the Mk I barrel, two polyethylene spiral strips (Somarite; manufactured by Somar Kogyo K.K.) 20 mm wide and 6 mm thick, were fixed to the barrel by screws. Their slope angle was 30° . The barrel was then machined to 120 mm OD, to make the clearance between the auger and the vertical strips about 0.8 mm to 1.5 mm. On the Mk II and Mk III

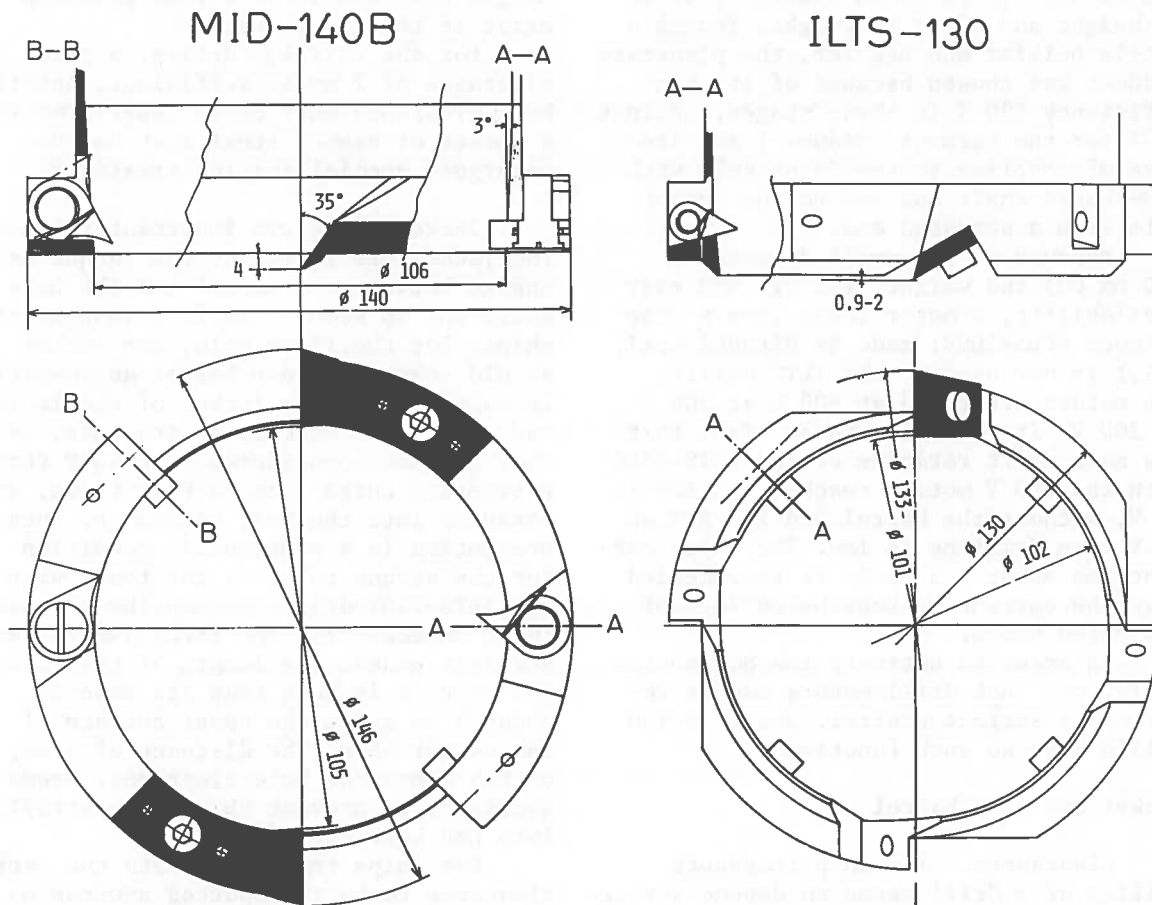


Figure 3. Cutter shoe assemblies of the MID-140B and ILTS-130C drills.

barrels, polyethylene spiral strips made of Solidur (manufactured in West Germany) 19 mm wide and 3 mm thick, were fixed in place with the adhesive tape used for attaching the vertical strips. Various auger slope angles up to 60° will be tried as fabrication is simple.

Cutters. The standard shape of the ILTS cutter is very simple: a flat, almost rectangular piece with one edged side as seen in Fig. 3. The Mk I and Mk II holders determine the bottom clearance angle as 30° and 25° respectively, while the Mk III holder, to which the cutters are reversely fixed, determines the back-rake angle as 40°. Cutters of hardened steel with various included angles varying from 30° to 50° have been supplied for the Mk I holder. The 45° cutters worked well for cold ice and firm but for drilling in wet ice, 30° angle cutters were necessary. Steel cutters are completely useless when drilling in ground ice with only a few percent by weight of silt present. Special cutters with a tungsten carbide tip were effectively used there. The clearance angle used was 15°.

Recently, tungsten-cobalt-carbon cutters with edges shaped by sintering have become available (K-20, made by Mitsubishi Kinzoku Kogyo K.K.). Cutters with included angles of from 30° to 50° are now being laboratory tested.

DESIGN SUGGESTIONS

The Anti-torque System

Escape device. When a drill with this system is to be used in an area where the drill may jam, it must have an escape device, such as the free wheeling safety cutters of the MID-140B. Motor driven safety cutters, not yet tested, may also be employed. A better solution is to make the guide fins retractable.

Extension unit. When passing through a thick weak layer of snow, where the drill rotated during the preceding run, the anti-torque system must be extended to bridge the thickness of the layer. (This idea was originally suggested for the Swiss drill by H. Ruffli). Auxiliary fins may also be temporarily placed above the guide fins.

Deep drilling. Where a cased hole is used, the pipe must have appropriate grooves for the guide fins.

Gravity drive. For a heavy drill, gravity driven side cutters (an application of the free wheeling cutters) may be worth consideration.

Drill Strength

Because it has been established that with the proper core breaker design, tensile forces of less than 2000 N are required to break core and torques less than 30 Nm are sufficient to cut the ice, the design strength values, especially of the barrel, may be reduced accordingly. The 2 m, Mk III, barrel will be made of 1.5 mm thick aluminum tube (1.46 kg/m). The 1.2 mm thick steel jacket of the ILTS-130A and C might not be sufficiently rigid, and could be replaced by an aluminum tube 2 to 3 mm thick.

Load Sensor

Because of their simple construction and reliable anti-torque system, the drills were not fitted with any monitoring devices. The torque and barrel rotation speed were estimated from the input current and voltage observed at the surface. A simple load sensor will be installed on the ILTS-130E unit. The signal will be frequency modulated and transmitted through conductors in the cable.

Hole and Core Size

Small sized core is attractive, because of its ease of breaking after a run. However, larger core may be necessary for reasons related to analyses to be made on the core. Some adopted (and suggested values) for the core, hole, inner barrel, and jacket diameters (in mm) are: (70, 95, 76.2, 88.9); (82, 107, 88.9, 101.6); (95, 120, 101.6, 114.3). A drill with the second set of values has been made and tested.

Armored Cable

The cable should be able to sustain a load of 2000 N and supply to the drill a current of 3 A (at 200 V) or 6 A (at 100 V). Suggested cables are Rochester 1-H-126K (3.18 mm ϕ , 41.7 kg/km, 6.67 kN tensile strength) for a 50 m system, and a 1-H-181K (4.72 mm ϕ , 95.4 kg/km, 15.8 kN tensile strength) for a 200 m system.

DESIGN OF A DRILL SYSTEM

The following equations will provide a guide for the design of the drills.

The time, t , required to drill to a depth D is

$$t = (D/L)(L/v + D/V + t_0) \quad (1)$$

where L is the core length, v is the drilling rate, V the winching rate and t_0 is a time constant dependent on the system design and the ability of the drillers. For a small system, a value of t_0 of several minutes is possible.

The barrel length, L^* and the core length, L are related by the equation:

$$k L (h^2 - c^2) = (L^* - L) d^2 + P \quad (2)$$

where k is the ratio of the density of ice against that of stored chips, h is the hole diameter, c is the core diameter, and d is the barrel inner diameter. P is a correction term for chips stored in the clearances. Putting

$2w = (h - c)$ and $2(r + d) = (h + c)$, taking $k = 2.5$ and neglecting small terms, the following simple and reliable relationship is derived:

$$L^*/L = 1 + 10 w/d \quad (3)$$

where w is the cutter width. For usual values of w and d , L^*/L has a value of 2 to 3.

For decreasing t , L is usually increased, but one must be sure that the drill can transport chips to a height L^* .

The necessary motor power output, P^* , of the drill is estimated from

$$P^* = E A v \quad (4)$$

where E is an energy per unit volume (taking typical values of from 5 to 7 MJ/m³) and A is the cutting area (m²). A very efficient drill may be associated with a value of E as low as 1 MJ/m³ (Mellor and Sellmann, 1976).

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THE PICO INTERMEDIATE DRILL SYSTEM

John Litwak, Leendert Kersten, Karl Kuivinen
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0200

Abstract

The PICO intermediate drill is an electromechanical drilling system designed for continuous coring in firn and ice to a maximum depth of 600 m in an open hole. The drill collects 10.2 cm diameter core in runs of 70-150 cm length. A new cutting head includes three bits and core-catching dogs. The surface components, mounted on a platform, include a Lebus winch with grooved drum containing 700 m of seven-conductor electromechanical cable, a dual tower device, a 2.5 kW motor for high-speed raising and lowering of the drill, a 1.25 kW motor for control of penetration and core break, and a control panel. The winch platform, operators and core processing station can be accommodated inside a modified Hansen WeatherPort shelter. A 30 kW, 208V AC turbocharged diesel generator powers the winch and drill. The total weight of the drill system including winch platform, drills, generator and shelter is 6600 kg.

Introduction

The design of the PICO intermediate-depth core drilling system was based on information and experience gained in the design, modification and operation of the USA CRREL shallow drill (Rand, 1976), NSF-Swiss drill (Rufli et al., 1976) and the RISP wireline core drilling systems (Hansen, 1976). The main design criteria for the PICO drill system were: (a) to drill as rapidly as possible through firn and ice to a maximum depth of 600 m in an open hole; (b) to collect

10-cm diameter core in runs 70-150 cm long; and (c) to be transportable between drill sites by LC-130 aircraft using minimal tracked vehicle support at each drill site.

The downhole portion of the drill was designed and built at PICO in 1979, and has been used in conjunction with other winch systems during the 1979-80 and 1980-81 seasons at South Pole Station to a maximum depth of 108 m. The winch platform was designed and assembled at PICO during 1981-82, and was used with the downhole components of the PICO drill during 1982 at South Pole Station to collect core to a depth of 237 m.

Components

The PICO intermediate drill system consists of the following components: the downhole coring drill; the cable; a platform housing a winch, tower and instrument panel; a shelter; and a generator.

The downhole component of the drill collects a 10.2 cm diameter core and cuts a 14.1 cm diameter hole. It can be used in either firn or ice in an open hole. The drill consists of an antitorque section, a motor, gear reducer, outer barrel and rotating inner barrel, and the cutting head.

The antitorque system consists of three leafsprings, 120° apart. Its function is to prevent the rotation of the outer barrel and motor section while contributing toward vertical stabilization and centering of the drill during

descent. Two sets of leafsprings are available for use in either firm or ice. The primary set has 3.175 mm thick x 25.4 mm wide skates of rectangular cross-section, having a double radius section of 35.5 cm and 40.6 cm, and an arc length of 81.5 cm. The material is 1095 carbon steel tempered to a C50-C56 Rockwell hardness. The second set of springs is made of 5056 steel, with identical radial configuration and temper, but with a 4.57 mm thickness x 35 mm width. Both sets of springs are available with square and 15° angle edges to provide options for use in various firm and ice conditions.

The drill is powered by a 440V, 3-phase motor which is regulated by a frequency controller that allows for a wide range of drill speeds (60-200 rpm) at the cutting head. The motor is coupled to a 17:1 cyclo-reducer, to provide adequate cutting torque, through a splined shaft that is coupled to the rotating inner barrel. Upon removal of a spacer ring, the combination of motor and gear reducer provides a hammer which can be used during penetration and core break. An optional 200V DC motor can be installed. It is encased in a protective barrel that prevents melting of snow around the motor section when the drill is used in warm ice. The controller used for the DC motor has a maximum output of 300V DC at 6 amps.

The aluminum cutting head houses the three cutters and three core-catching dogs. The function of these core dogs is dual: to create regions of stress concentration for ortho-axial core break, and to hold the core inside the inner barrel during the raising of the drill. An internal taper of the cutting head assists in gripping the ice core. The cutters and core dogs are made of 440-C stainless steel.

As the inner barrel and cutting head rotates, penetrating over the core, the chips are carried up two spiral flights fixed to the outside of the barrel. A reverse spiral at the upper end of this barrel forces the chips through a port where they fall into a chamber above the core. The spirals are made of ultra-high molecular weight polyethylene attached to the inner barrel by screws.

The electromechanical cable is a Vector A10182 standard logging cable with seven conductors, each #20 AWG or 0.36 mm diameter with Tefzel insulation. The breaking strength is 59600 N and the cable weight is 0.42 kg/m. Although

the catalog specifies a 1.0033 cm outside diameter, a design value of 1.05 cm was used when specifying the winch drum. The cable is terminated and joined to the top end of the drill by an IEC slip-ring assembly that eliminates twisting of the cable if the drill section should spin downhole during antitorque failure.

The winch platform houses the winch, tower assembly and control panel. The 2.36 m x 2.49 m aluminum platform is supported by three wide-flange skis, and has four levelling jacks for use in positioning and stabilizing the unit during drilling. The winch, tower and control panel are bolted to the platform, and for transport or storage the entire unit is encased in an angle-iron and plywood container.

The Lebus winch has a drum grooved with 19 wraps between flanges that allows for orthocyclic winding of the cable. The drum capacity is 700 m, of which 600 m is available for use downhole, with the remaining 100 m providing a base wrap.

The winch drive system for lowering and raising the drill, and the drive mechanism for the control of penetration rate and core break, are permanently attached to the platform. A 2.5 kW permanent magnet motor coupled to the winch drum through a 54:1 hub reducer provides controllable line speeds from 15 cm/sec to 1 m/sec for raising and lowering the drill. A 1.25 kW permanent magnet motor is coupled to the main shaft through an electromechanical clutch, the 54:1 hub, and an 11:1 reducer with a 2:1 sprocket ratio. This provides delicate control of the drill's penetration rate and enables the operator to control core-break line tensions and speed whenever difficult core break situations arise. Speed control over this motor creates line speeds from zero to 5 cm/sec. The maximum line tension at low speeds is 49000 N. Both motors have regenerative braking, although this feature is intended for use only on the 2.5 kW motor system. On the side of the 54:1 hub reducer and directly attached to the drum is a disk brake, while on the opposite side an 8-conductor, 500V AC, amp, slip-ring is mounted on the shaft. The brake unit is mounted on a location allowing for easy inspection/servicing, and functions as a locking device or a drag-stopping brake.

The dual tubular steel tower system, 9.144 m long, can be assembled by

joining five 1.83 m sections per tower in the horizontal position. The two tower sections are held together by a top connecting bridge upon which is centered the grooved sheave. Sheave cleaners and cable restraints are included on the sheave assembly to keep the sheave free of ice and the cable in place during high-speed raising and lowering of the drill. A two-point reactive load system provides a direct reading of the cable tension by way of a load cell on one side of the bridge. The sheave shaft is connected to a bi-directional depth counter and line speed indicator. After horizontal assembly the tower is raised to the upright position through use of a linkage system and cable grip hoist. The dual tower provides a rigid structure and allows the drill to hang free between them. The use of a 9.144-m tower system eliminates the need for a fleet angle compensator to be used in winding the cable on the drum. The high tower also allows the drill to be kept in the vertical position at all times, thereby reducing the risk of bending components, and eliminating the requirement for a pit or trench for use during removal of the inner barrel after each run. At the base of the tower, on the winch platform, is a combination cable guide and hole cover through which the cable passes. This device assures vertical alignment of the cable as it passes over the 60.9 cm diameter top sheave, through the platform, and down the borehole.

All instruments for the control and monitoring of the winch and drill are grouped on one panel, mounted 1 m above the platform surface overlooking the winch drum, tower and hole opening. Inside the heated panel are housed all necessary transformers, chokes and electronic equipment. Gauges are provided that allow the operator to monitor continuously the winch and drill current and voltage.

The generator is a 30 kW, 3-phase, 208-120V, 60 Hz unit, using a turbo-charged diesel engine proven operable at elevations up to 3700 m. The generator is mounted on skis for towing over the snow surface. A plywood shelter is used to ensure adequate cooling of the engine and to prevent blowing snow from entering the control panel.

A modified Hansen WeatherPort with arch dimensions of 4.57 m wide x 12.2 m long x 2.05 m high and covered by a 6-piece canvas cover, protects the winch

system and drill operators from wind and blowing snow, and provides a core processing work area.

Drilling Program at the South Pole, 1982

The 1982-83 antarctic field season provided the first opportunity to test and use the complete intermediate drill system in a field situation.

Drilling took place in the center of the taxiway oval at Amundsen-Scott South Pole Station. The drill, platform and shelter were set up on a wooden platform after drifted snow and the past year's accumulation were removed from its surface (see Figure 1). A core processing and science trench (3 m deep x 3.5 m wide x 15 m long) was excavated parallel to the drill shelter, roofed with timbers and plywood, and a stairway and tunnel were constructed which served to connect the drill platform with the science trench. It took four people 2.5 days to assemble, erect and supply electrical power to all surface components of the camp (generator, two laboratory vans and the drill shelter).

Drilling started at a depth of 108 m in a hole drilled by PICO in 1980-81 with the same downhole drill. The DC drill motor was used all season. Bits with a 45° cutting angle were used first. These produced very fine chips which packed around the core inside the inner barrel, and caused the core to be twisted off at the base before completing a run. Attempts were made to remedy the problem by reducing the clearance between the core and inner barrel wall, increasing the cutting angle of the bits to 55°, and sharpening the cutters, but problem persisted.

Cutters with a 78° angle from horizontal and no adjustments for penetration eventually produced good core in 70-cm runs with penetration rates of .5 cm/sec to a depth of 215 m. Thereafter, core quality deteriorated, with frequent cracks and wafering occurring, and with the length of runs reduced to 30 cm and less. Unsuccessful attempts were made to drill using a new head and bit configuration designed and built at the University of Bern. Problems encountered with this head were that penetration was limited to 10 cm/run due to chips packing behind the cutters, and that packing around the core dogs resulted in failure to catch the core. Drilling was finally stopped

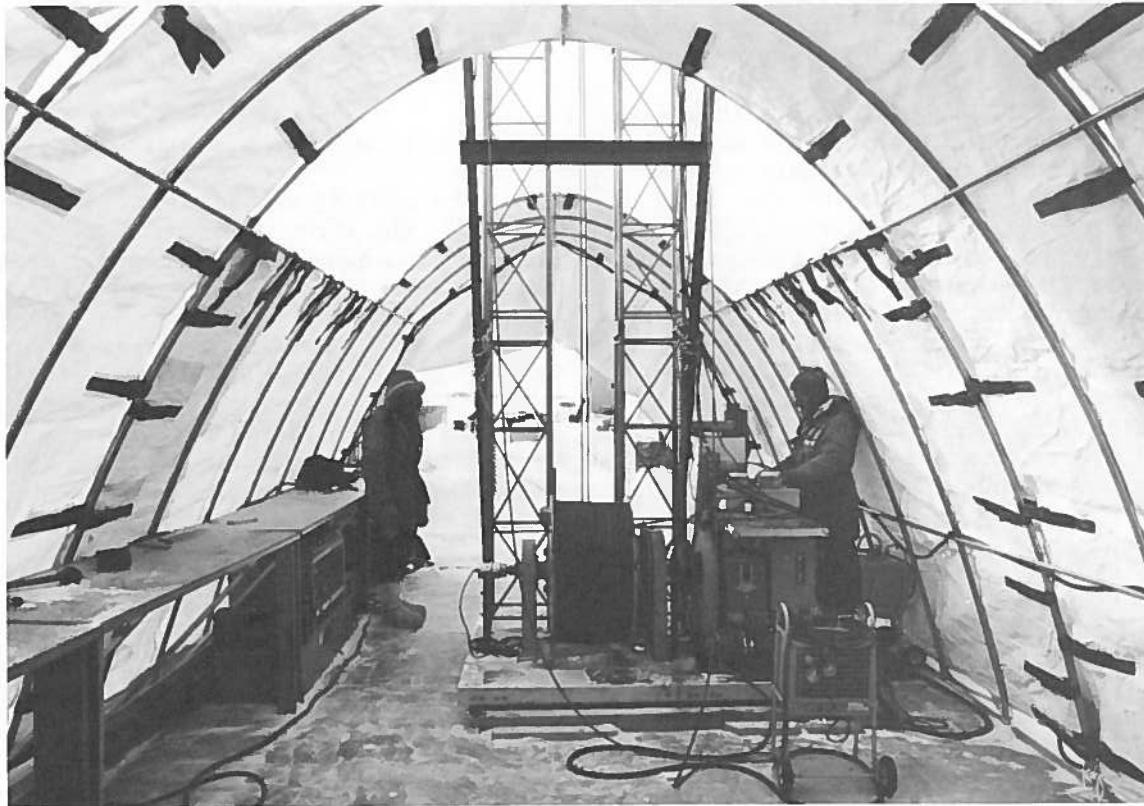


Figure 1. Winch platform including winch drum, tower assembly and control panel inside the canvas-covered drill shelter at the South Pole, December 1982.

at a depth of 237 m.

In summary, the new winch and drill system worked well; we experienced no mechanical failures, and only one electrical problem with the load cell readout which was later bypassed. The tower system took 6 manhours to assemble, yet was erected easily, provided a stable tower throughout the one-month season, and simplified and expedited the removal of the inner barrel after each run. The drill shelter with its 6-section canvas cover and Velcro tie-down straps was easily erected in 8 manhours, and provided a satisfactory windbreak throughout the field season. The drill head and bit designs are being reviewed, and will be redesigned or modified to provide improved core quality, penetration rate, and run length in the system's next field application.

Acknowledgement

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RECENT EXPERIENCES WITH A MODIFIED RUFOLI ICE DRILL

Hans L. Jessberger and Rudolf Dörr
Department of Civil Engineering
Ruhr University, Bochum
West Germany

ABSTRACT

An electro-mechanical shallow depth ice core drill was built, with a few modifications, following the general *Rufli* ice drill design. Our equipment was tested in October, 1981 on a glacier in the Alps before it was shipped to Antarctica. The drill will be used to take ice cores from the ice shelf near the Georg von Neumayer station for mechanical and chemical investigations. *In situ* systems for measuring the deformation behavior of the shelf ice will be installed in the boreholes. Details of the drill, together with our experiences during drilling, are described.

INTRODUCTION

Boreholes are necessary in order to investigate the deformation behavior of shelf ice with depth by *in situ* measurements, and to procure ice cores for mechanical and chemical investigations. The layout of the equipment depends primarily on the drilling depth required. During the 1980/81 German expedition, boreholes down to 15 m depth were drilled in connection with measuring settlements of the Georg von Neumayer wintering station and the Filchner summer station using the SIPRE drill driven by a motor. For greater depths, this drill was not sufficient.

Electro-mechanical ice drilling systems for depths greater than 100 m have been developed by Rufli (1976) and Rand (1976). H. Rufli, University of Bern, Switzerland, helped us with the drill design, construction and the first

tests. With this support it was possible to finish the shallow drill construction in half a year, so that it could be used during the 1981/82 Antarctic Expedition near the Georg von Neumayer station. Prior to this expedition, the drill was tested at the Kitzsteinhorn/Kaprun (Austria).

THE SHALLOW DRILL SYSTEM

Figure 1 shows a view of the electro-mechanical drilling system during the tests. The drill may be subdivided into the following parts:

- (a) Drill with motor and anti-torque section
- (b) Winch, including cable
- (c) Electronic control system
- (d) Mast with pulley.

The individual components are now discussed.

Cutter head, motor and anti-torque section

These parts are predominantly copied from the *Rufli* ice drill. The total length from the cutter head to the top of the anti-torque system is about 4.70 m. The cutter head (Fig. 2) is made of aluminum. Three bits that cut a core of 7.5 cm diameter are fastened to it equally spaced over the perimeter. The diameter of the borehole is 11.7 cm, which means that an annulus of 4.2 cm width is cut away by the blades. The shape of the bits used first were the



Figure 1. View of the drill system.

same as those of the SIPRE drill, because lack of time prevented testing other bits. Two core catchers, 3 mm wide, are also fastened at the cutter head, but during drilling the width of the core catchers was found to be too small because of the notch effect in the core. The core catchers are pressed against the core by a spring.

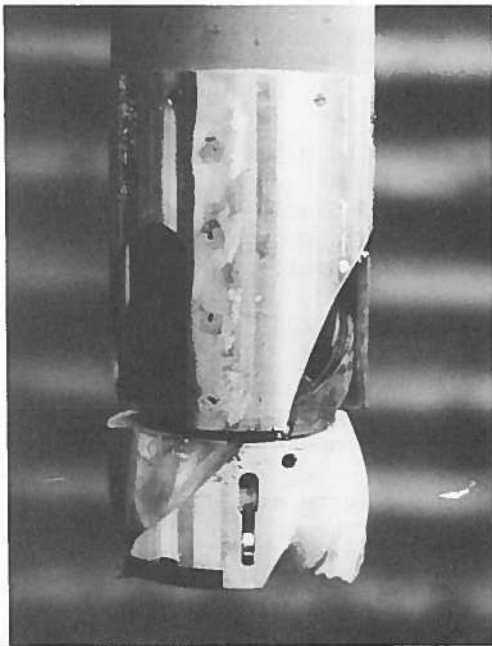


Figure 2. The cutter head.

The cutter head is fastened to the 2.20 m long core barrel. This is a PVC

coated steel tube of inner diameter 81 mm. Two PVC spirals are screwed to its outside surface. These spirals transport the chips to two inlets at the upper end of the core barrel. To prevent chips from lodging around the core, a *Rufli disc* is used. This slides within the core barrel above the core.

The core barrel is inserted into an outer barrel (106 mm internal diameter; 110 mm external diameter) and fastened at the gear and motor section. This steel tube is coated with a light colored PVC layer to prevent heating by solar radiation. The coupling between the core barrel and the motor unit is identical to that described by Rufli (1976) and consists of a lever-spring system.

The 450 W, 140 V DC motor runs at 3000 RPM which is reduced 1/17 by a gear unit to give a maximum speed of the cutter head of about 175 RPM. The speed of the motor is measured by a tachometer and indicated at the control panel. The current is transmitted from the cable to the motor using a sliding copper connection inserted in a PVC frame.

The anti-torque system (Fig. 3) used in this drill is based on the Swiss design. To prevent the drill from turning relative to the borehole wall, three steel knives are pushed against the wall to oppose the torque from the cutter head. The pressure of the knives against the wall increases with the turning moment of the drill. The knives move within slides to which adjustments can be made.

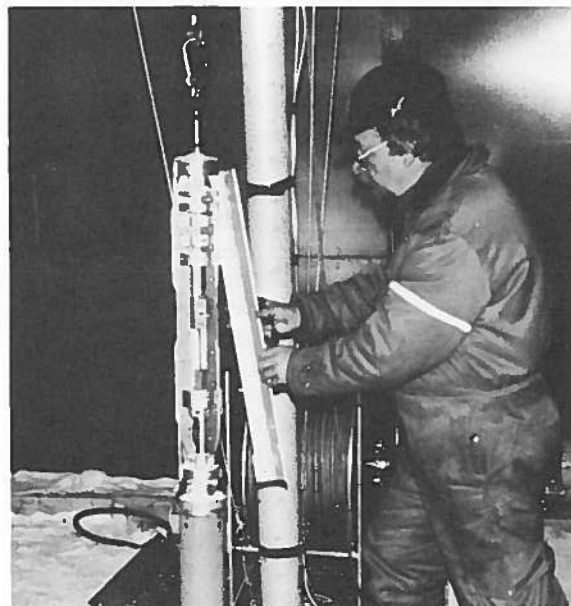


Figure 3. The anti-torque unit.

Cable and winch

The steel armored cable has seven conductors and is manufactured by the Norddeutsche Seeabelwerke, Nordenham, West Germany. It has a diameter of 10 mm with an area of 0.35 mm^2 for each conductor. It weighs 27 kg/100 m. The seven conductors are used in the following way: one pair for the current to the drill motor, one pair for the speed sensor for the drill motor, one pair for the strain gauge positioned inside the anti-torque section, and one conductor for ground.

The tensile strength of the cable is about 3600 kg. The connection between the drill and the cable is welded. Twisting of the cable is prevented by a safety hook. The bending radius of the cable is restricted to 25 cm.

The winch (Fig. 4) is mounted on a ground plate and connected to the mast. The drum has a diameter of 50 cm and is driven by a 140 V DC motor to a maximum speed of 3000 RPM. The speed is gear reduced by 1/71 and further reduced by two pulleys connected with a cone belt to 1/3 for a total reduction of 1/213. This speed can be continuously adjusted by a motor controller on the control desk. All parts of the winch are dimensioned for the maximum tension of 3600 kg. This resulted in a total weight of about 250 kg in spite of using aluminum in the construction.

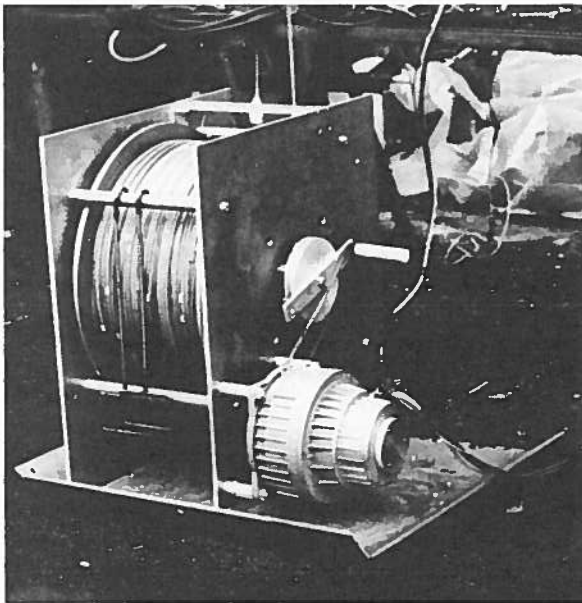


Figure 4. The winch including motor.

Mast and pulley

The mast of the drill (Fig. 1) is composed of two aluminum tubes with a length of 2.30 m, including the pulley. The total height of the system is 5.50 m. The base of the tower rests on a ball joint fixed to a 0.90 m square base plate, which is connected to the winch base plate. The mast can be anchored by three guy wires. The outer diameter of the tube is 120 mm and the inner diameter 114 mm. It is possible to transport the motor and the anti-torque section inside these tubes to economise on space and to prevent them from damage during transport.

The pulley, with a diameter of 50 cm, is fastened to the top of the mast. The depth of the drill is determined by counting the passage of magnets positioned around the circumference of the pulley. An accuracy of ± 10 cm was achieved, but this seems to be insufficient to determine the position of the cutter head satisfactorily.

ELECTRICAL SYSTEMS

General data

On the one hand, the electrical system can be based on sophisticated electronic technology. On the other hand, the possibilities for repairing these parts in Antarctica are very limited. Therefore, two systems were developed with different methods of operation: a system with motor controllers and a system with electrical resistances. Both systems use 380 V three phase current with a minimum power of 3kW.

Motor controller system

Using this system, a desired value for the speed of the winch motor or the drill motor can be adjusted on the control panel. The current intensity needed to keep this value constant is regulated automatically. The electronic parts are contained in two boxes. The first contains an easily transportable control unit (Fig. 5a) that is connected by cables with the second box that contains all necessary electrical circuitry (Fig. 5b). These parts weigh 200 kg. Because some parts of the electronic system require a temperature above 5°C , a 2 kW thermostatically controlled heater is installed inside the

second box. During operation, the electronic parts produce enough heat energy to keep the temperature above this level.

The following information may be read off at the control panel:

- (a) speed, current and voltage draw of the drill motor and the winch motor
- (b) the depth of the drill
- (c) the tension in the cable
- (d) additional information about the temperature levels inside the electrical system can be monitored by a multi-colored light display.

System using electrical resistances

Electrical resistances are used for controlling the drill motor, the winch motor and the electrical brake. All parts of this system including the indicating meters are installed on one control panel that can be easily transported. Operating this system is not as convenient as the other system, but it may be repaired more easily. This unit was also tested during the expedition and was found to operate satisfactorily.

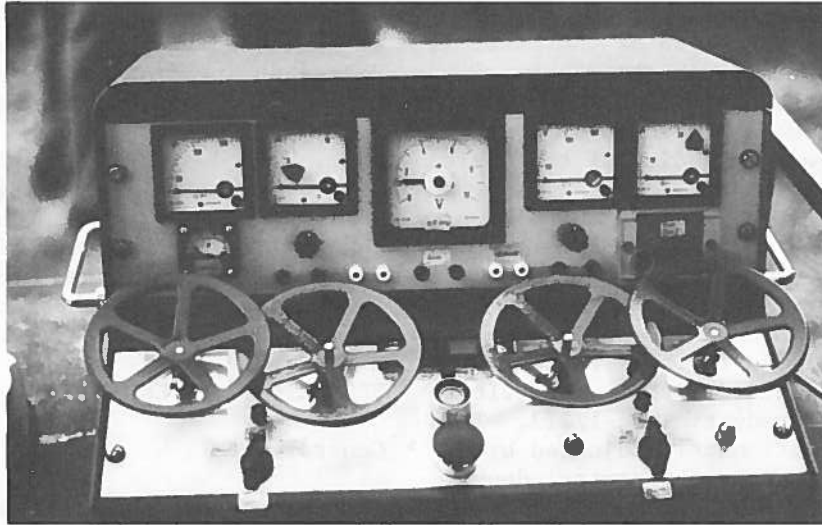


Figure 5a. Control panel for the system with the motor controller.

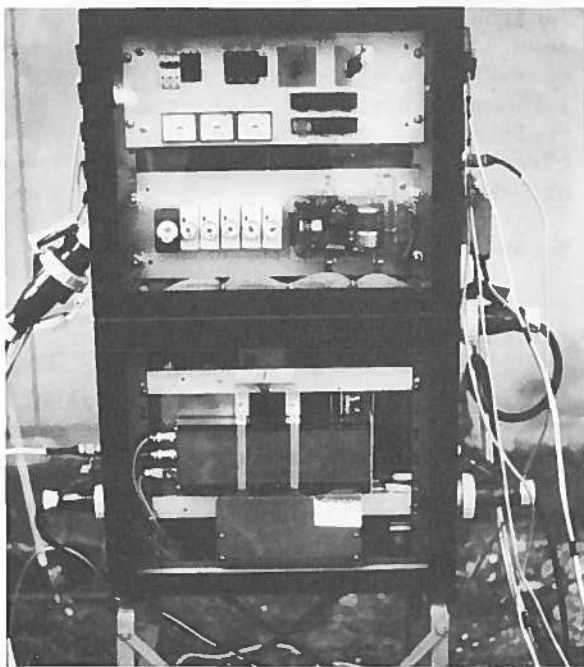


Figure 5b. Electronic rack for the system using motor controllers.

The information indicated on the second control panel is the same as before except the depth measurement is missing.

DRILLING DURING THE 1981/82 EXPEDITION

During the 1981/82 season the drill was deployed for two reasons:

- (1) to obtain *in situ* measurements of the deformation behavior of the Ekstrom Ice Shelf, and
- (2) to retrieve cores from those boreholes for mechanical and chemical investigations.

The conditions during drilling were good because of the proximity of the Georg von Neumayer station. The drilling took place inside a newly built shelter. Only the drilling time was restricted because of the installation of the measurement system into the boreholes and of additional research projects on the Filchner Ice Shelf. The borehole depths and the drilling times are shown as follows:

<u>Borehole</u>	<u>Depth</u>	<u>Dates</u>
B 3	73.60 m	13-17 Jan. 1982 (includes tests)
B 4	51.65 m	26-27 Feb. 1982 (12 hours drilling)
B 5	20.00 m	27 Feb. 1982

During the drilling of the B 3 borehole the quality of the ice core was unsatisfactory because of "discing" of the core below 45 m depth. By re-grinding the blades better results were obtained. At B 4 these difficulties did not appear.

The inclination of the borehole was later measured and at a depth of 45 m in B 3 an increase in slope of 0.5° was found. This possibly had an effect on core quality at this depth and below.

IMPROVEMENTS TO THE DRILL

The experiences derived from the 1981/82 expedition resulted in some improvements to be made in the drilling equipment. Those improvements are as follows:

- (a) the installation of a new Kevlar armored cable with a weight of 13 kg/100 m and a breaking strength of 1000 kg.
- (b) the manufacture of a new winch for this cable. This weighs about 100 kg.
- (c) the installation of another anti-torque system using plate springs as used by Rand (1976), Gundestrup *et al* (1984) and Holdsworth (1984).
- (d) the use of another depth measurement system using a mechanical device.
- (e) several improvements were made to the electrical system to improve control of the motors.

This new drill will be used during the 1982/83 Antarctic expedition.

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NEW HORIZONS IN DRILL DEVELOPMENT

Bruce R. Koci
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0200

Abstract

New materials for cables and cutters are discussed in relation to lightweight and efficiency. Kevlar, used as the strength member in an electromechanical cable, reduces weight by 70 percent and allows the use of smaller diameter sheaves and winches. Efficient cutters and core breakers are discussed along with a selection of materials suitable for drilling in cold ice. Use of small diameter hermetically-sealed heaters in a ring are also discussed to complete this 200 m system which can be backpacked into remote areas. This drill can take 7.6-cm or 10-cm diameter cores in lengths varying from 1- to 2-m. The approximate weight of the system is 400 kg and the cube is 1.2 m³ with minor variations depending on which drill is chosen.

Introduction

Recent developments in materials and power sources have increased depth capability of electromechanical drills while reducing the weight and power requirements. Materials developments include Kevlar reinforced cables and steels for cutters that are hard without being brittle at low temperatures. This design flexibility has made it possible for PICO to develop a 200 m drill that can be run on solar power and which can be backpacked into remote areas.

Materials and Power Sources

The importance of drill bit design

and core dog shape is critical in lightweight drill design. Refinements in drill bits have reduced power requirements to the 400 watt range, allowing the use of torquing motors and eliminating the requirement for a gear reducer. As a result, weight is removed from the upper end of the drill, making the system more stable. Currently, the motors have a torque capacity of 22 N-m at 180 rpm. Each motor weighs approximately 4 kg. Selection of a proper core dog shape is critical to keep the winch, cable and tower compact and light. Core breaks in ice at South Pole Station during the 1981-82 season were reduced from 3000 kg to 250 kg by the use of newly-designed core dogs (Figures 1a and 1b).

Optimum core dog design is similar to proper bit design in that a minimum amount of energy is desirable to cause fracture. Generally the bisector of the point angle should enter the core at an angle of 30°. If the included angle of the point is chosen as 30°, then any upward force is multiplied by two. Additionally keeping the point very sharp can cause a stress concentration factor of 3. When the core dogs are working properly, the bottom of the core should have a slightly concave shape since the initial fracture will start with an upward component. Selection of rounded surfaces make the core dogs penetrate more easily than flat surfaces based on our field tests.

Material selection for core dogs is not critical as long as the points are kept sharp. Use of stainless because of

its resistance to embrittlement in cold ($T < -20^{\circ}\text{C}$) is suggested for the core dog pin.

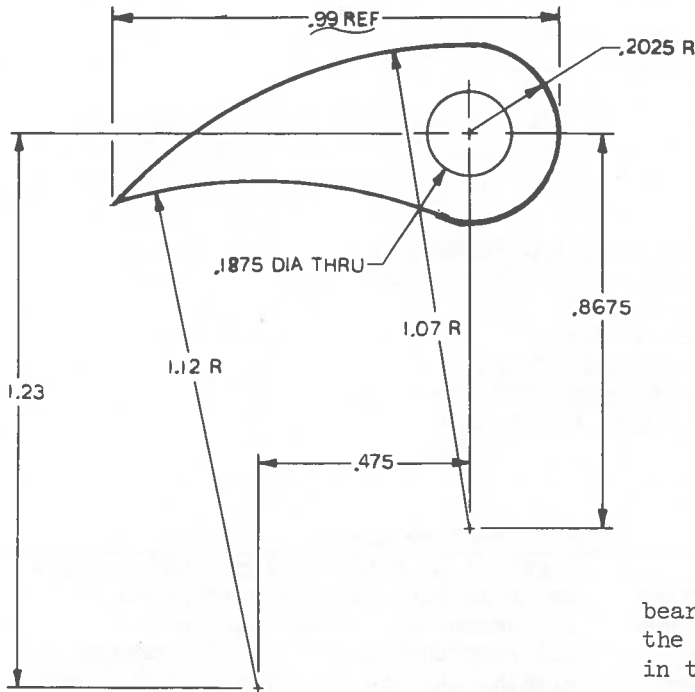


Figure 1a. Core dog

Proper materials selection for cutters is essential. The presence of carbon in most tool steel causes brittleness as the temperature drops below -20°C . Maraging steels, 440 stainless alloys, and high cobalt tungsten carbide alloys show promise in providing hardness and toughness. Evaluation of these materials in -52°C ice at South Pole was completed this past season. A-2 tool steel was found to be the best of available tool steels since it did not chip as readily as the high speed steels. The 440 C stainless and maraging grade of steels were slightly better in resistance to chipping and could generally be kept sharper. The 25 percent increase in materials and machining costs thus becomes questionable.

The hard but brittle nature of cold ice suggests a need for self-centering bits that provide bearing surfaces to keep from shattering the core. Round cutters are superior in this respect but require a higher bit pressure to penetrate increasing the likelihood of drilling a crooked hole. A more promising design is suggested in Figure 2. Note the lead angle has been increased from 45° to 50° for -50°C ice suggesting an increase in clearance angle from 10° to 15° to maintain a "fine" wedge shape.

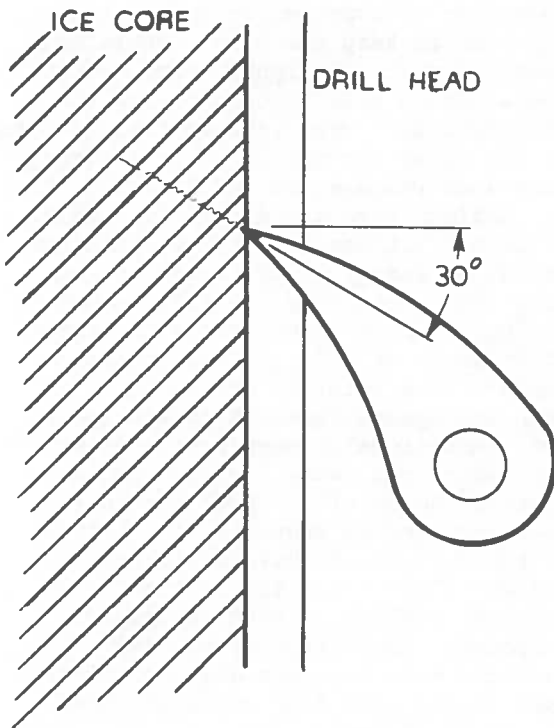


Figure 1b. Core dog position relative to ice core

A key element in this package is the Kevlar reinforced electromechanical cable. This cable with 7 #20 conductors and 3000 kg breaking strength weighs about 13.2 kg/100 m compared to 39.6 kg/100 m for a similar steel-reinforced cable. The reduction in weight is possible because Kevlar fibers are ten times as strong as steel wires when compared on a weight basis. The relatively low shear strength of the Kevlar fibers suggests caution in their use.

In addition, this cable has a bending diameter of 30x the cable diameter (1 cm) which reduces component size requirements by a factor of nearly two. Termination problems with this type of cable have been eliminated in recent years and have resulted in a termination strength of 100 percent of cable strength.

The use of composite inner and outer barrels, similar to the barrel used on the PICO lightweight hand auger, diminishes drill weight without sacrificing performance in ice

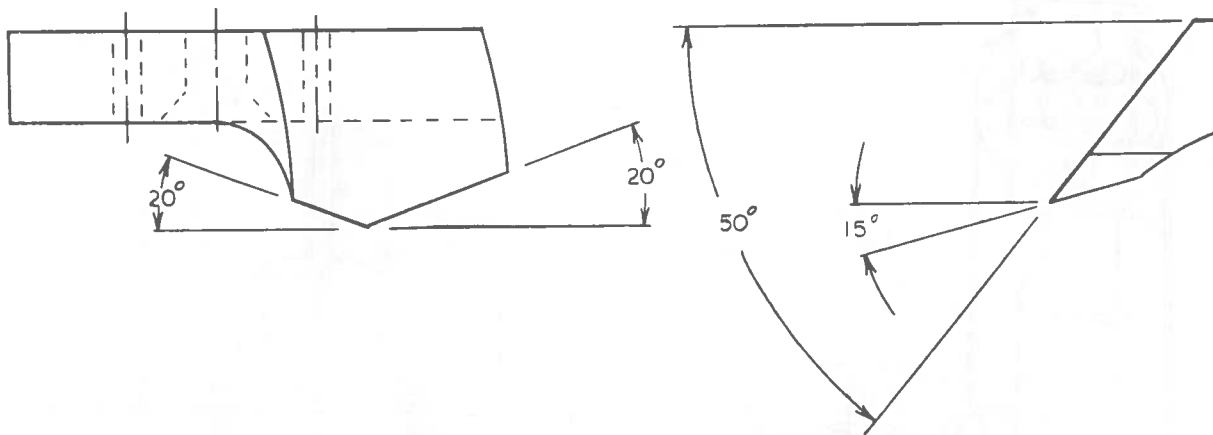


Figure 2. Self-centering bit

above -25°C . The inner barrel is constructed exactly as the hand auger barrel is, while the outer barrel has ribs on the inside formed as an integral part of the tube.

Since this drill has been designed as a system, we are adding the capability of electrothermal coring. Hermetically-sealed heaters of less than 1.5 mm diameter and watt densities as high as $100\text{W}/\text{cm}^2$ are brazed to a stainless steel ring, and provide a penetration rate greater than 4 m/hour with approximately 1200-watt power input. The core diameter in this case is 8.5 cm while the melted hole is approximately 10 cm.

By reducing the drill weight and core break requirements which we demonstrated at South Pole Station during 1981-82, power and torque requirements are kept small. This allows the use of small gear reducers and standard motors, or a pair of 135 N-m torquing motors that weigh about 10 kg apiece. Thus, all components of the winch package weigh less than 20 kg, and will each fit into a backpack. Drawings of the winch and tower are given as Figures 3, 4, and 5. A tensile structure is used as a shelter since the weight is less than 20 kg while providing adequate wind resistance.

Since the power requirements are on the order of 1000 watts, the possibility of using solar power becomes realistic. Twenty-five 37-watt panels will provide the required power since each produces about 45-watts because of the ultraviolet light reflected from the snow surface. These Solarex panels are .7 m square and weigh approximately 5 kg each.

This drill development is supported

by the National Science Foundation under contract DPP74-08414 with the University of Nebraska-Lincoln, Polar Ice Coring Office.

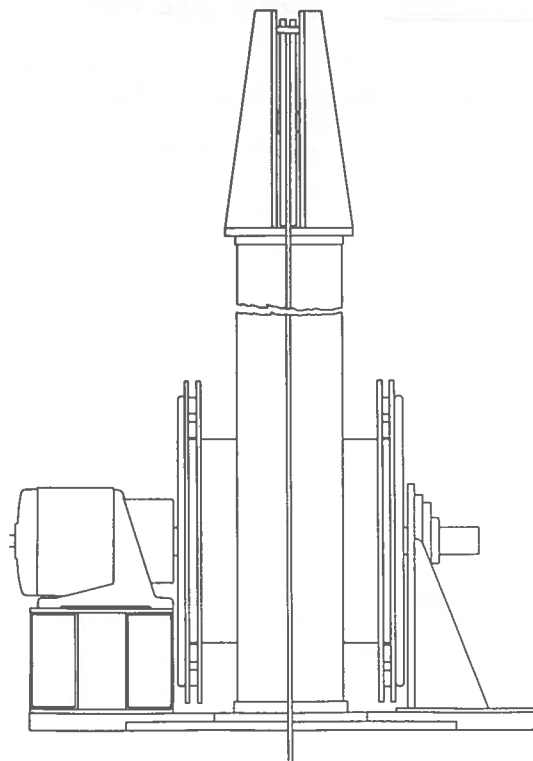


Figure 3. Winch: Front View

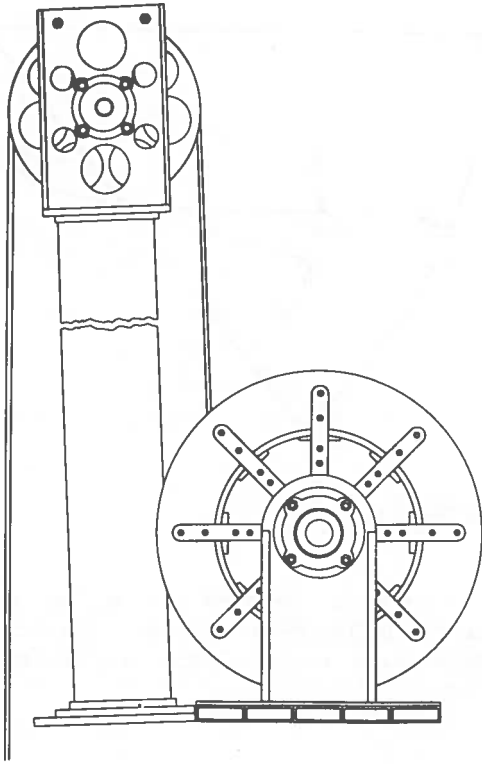


Figure 4. Winch: Side View

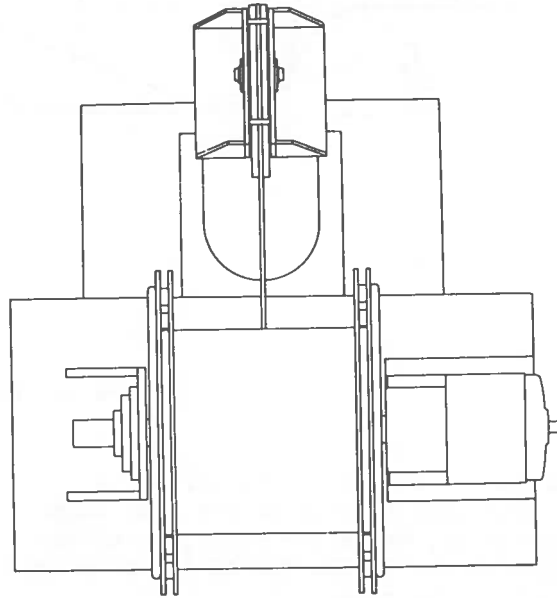


Figure 5. Winch: Top View

A LIGHTWEIGHT HAND CORING AUGER

Bruce R. Koci
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0200

Abstract

Extensive use of glass epoxy composites has allowed the design of an auger capable of drilling to 30 m without the use of a tripod, or to 50 m with a tripod to assist in raising the drill string. Approximate weight of a 10-m drill is 10 kg. Since most of the drill is already made of plastics, applications for making a "clean" drill are also discussed. Further refinements using solar voltaics and more exotic materials to ease the drilling burden are discussed. This drill has been tested in Antarctica, Greenland and the Peruvian Andes to near its proposed depth limit.

Introduction

The PICO lightweight hand coring auger is designed for ice core drilling in high-alpine, remote locations where it is difficult to transport and use heavier augers and electromechanical drills. The PICO auger has proved itself as a viable alternative to the SIPRE auger in most coring applications to depths of less than 50 m.

The PICO hand auger is built entirely out of materials with high specific strengths. The core barrel, extensions, T-handle and tripod are made of commercially available fiberglass composite pipe (Figure 1). Fittings, adaptors and cutting heads are machined from aluminum. Shipping and carrying containers are canvas duffle bags. The few tools necessary to service and maintain the auger are available

from most hardware stores.

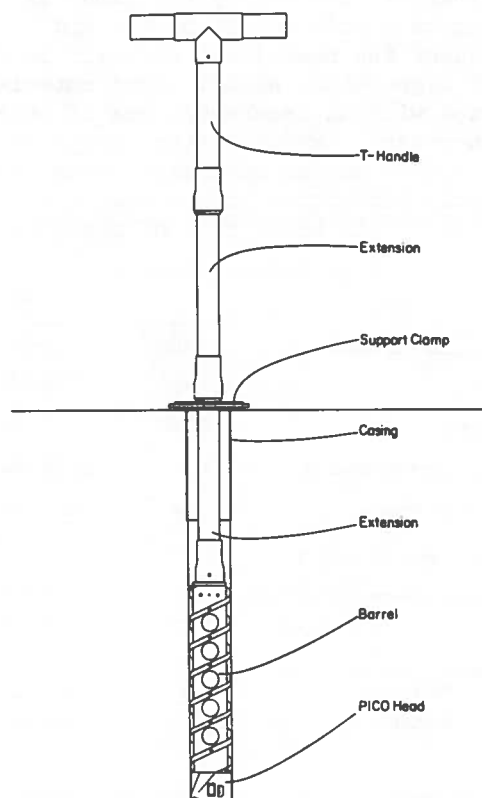


Figure 1. Lightweight hand auger with casing.

Drill Description

The use of composite materials, with their favorable specific strength, has increased hand augering depth capability to the 50-m range. Traditional SIPRE auger cutting heads

and bits have been redesigned to include core dogs which enhance core-catching capability. This drill system has been used with an electric motor and solar voltaics as a power source to decrease drilling time while avoiding contamination of the snow surface otherwise associated with gasoline-powered generators.

The concept of using glass-reinforced composites in drills and extensions is neither new nor unique in glaciological applications. However, the unique properties of composite materials and current mass production practices has made it desirable from structural and economical viewpoints to use these materials in drilling applications.

Table 1 makes it readily apparent that composites exhibit superior specific strengths and specific modulus where compared with aluminum or steel. Kevlar and graphite are nearly ten times as strong on a unit weight basis, and represent the near ideal solution to a truly lightweight drill. Both materials are not without drawbacks, one of which is increased costs. Custom layups of composites require special tooling and assembly techniques, resulting in a cost of five to six times that of standard

water pipe of E-glass or S-glass and epoxy. A more detailed description of the auger's components is provided below.

The core barrel, available in either 1- or 2-m lengths, is a piece of 7.5 cm diameter composite pipe wrapped with two ultrahigh molecular weight polyethylene spirals cut from sewer pipe and riveted to the barrel. An aluminum adaptor, held in place by quick-release pins, is used to connect the core barrel to the extensions.

The extensions are 5-cm diameter composite pipes which are cut to either 1- or 2-m lengths, and with weigh 1 kg and 1.5 kg per extension, respectively. Since it was recognized that nearly all the strength benefits of composites are lost when the glass fibers are cut, a design problem was encountered in determining the method to be used to join the extensions. Screw threads were decided upon as being the least expensive alternative since other attachment methods involved more intricate mechanisms and heavier components. The screw threads are modified ACME threads which are used commercially to join lengths of composite water pipe. The strength of the joints and pipe used in the lightweight auger are thus more than

Material	Density gm/cm ³	Modulus of Elasticity MPa	Ultimate Tensile Strength MPa	Specific Modulus 10 ⁸ cm	Specific Tensile Strength 10 ⁶ cm
Steel	7.85 ^{1}	206,800 ^{1}	448 ^{1}	2.7	3.2*
Aluminum	2.78 ^{1}	73,100 ^{1}	310 ^{1}	2.7	1.1
Glass Epoxy Composite	1.84 ^{1}	39,300 ^{2}	1100 ^{2}	2.6	5.8
Kevlar 49 Fibers	1.44 ^{3}	131,000 ^{3}	3447 ^{3}	9.1	24.0
Kevlar-Epoxy Composite	1.38 ^{3}	75,800 ^{3}	1380 ^{3}	5.5	10.0
Graphite Fibers Fortafil 3	1.71 ^{2}	206,800 ^{2}	2482 ^{2}	17.5	14.5
Fortafil 5	1.77	331,000	2758	18.7	15.6
Graphite-Epoxy Composite Fortafil 3	1.52 ^{2}	117,000 ^{2}	1034 ^{2}	7.7	6.8
Fortafil 5	1.53	186,200	965	12.2	6.3

Specific Modulus = Modulus of Elasticity ÷ Density

Specific Tensile Strength = Ultimate Tensile Strength ÷ Density

*Strands of wire cable.

{1} Baumeister, T. et al., 1978.

{2} DuPont, Wilmington, Delaware.

{3} Great Lakes Carbon Company, New York, 1980.

Table 1. Comparison of material properties.

adequate for this application. One advantage of using screw threads is that nothing sticks out beyond the O.D. of the extensions, such as quick-release pins would, thereby eliminating the problem of chips being scraped off the hole wall. As a result, the core length capability is not decreased due to the barrel filling up with the chips from the hole wall. The extensions can be easily detached in 1-12 m increments (Figure 2).

Tests in Greenland during the past two seasons have demonstrated the capabilities of this drill. By using the 2-m core barrel, cores ranging between 1.2 m and .8 m are retrieved each run. As a result, 20 m holes can be drilled in half a day, 30 m in one day, and 40 m in less than two days. Depths beyond 40 m require the use of a tripod and a strong desire to go deeper.

A new cutting head has been designed to incorporate both a tapered annulus and core dogs to insure positive catching of the core after each run. Additionally, the leading angle of the cutters has been made more shallow (45°) for easier cutting. Adjustment

screws are necessary to control the rate of penetration and to avoid jamming the drill (Figure 3). While the current heads are made of aluminum and steel, alternative materials are available to avoid contamination of the core. A Delron or Nylon head with tungsten carbide cutters is one example.

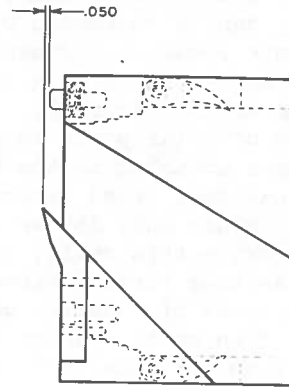


Figure 3. Cutting head showing adjustment screws.



Figure 2. PICO driller with 9 m of extensions.

Accessories

The use of a tripod to assist in lifting the drill string increases the depth capability of this system to 50 m. A block and tackle is used to multiply the lifting force by four. By using a casing around the top of the hole and clips which rest on the casing, the drill string can be suspended while extensions are removed, further relieving the burden of raising and lowering the drill (Figure 4).

The use of solar power to drive an electric motor attached to the topmost extensions has been tried successfully (Figure 5). Since only 250 watts are required to drive this drill, the motor package is neither large nor heavy. Penetration rates of 1 cm/sec were achieved in firn at 40 m depth on a sunny day, with the rate being reduced by half on a cloudy day.

The weight of this drill in its current state is as low as .75 kg/m per extension, added to 3 kg for the drill barrel and head.

The design and manufacture of the PICO lightweight hand coring augers is supported by the National Science Foundation Division of Polar Programs

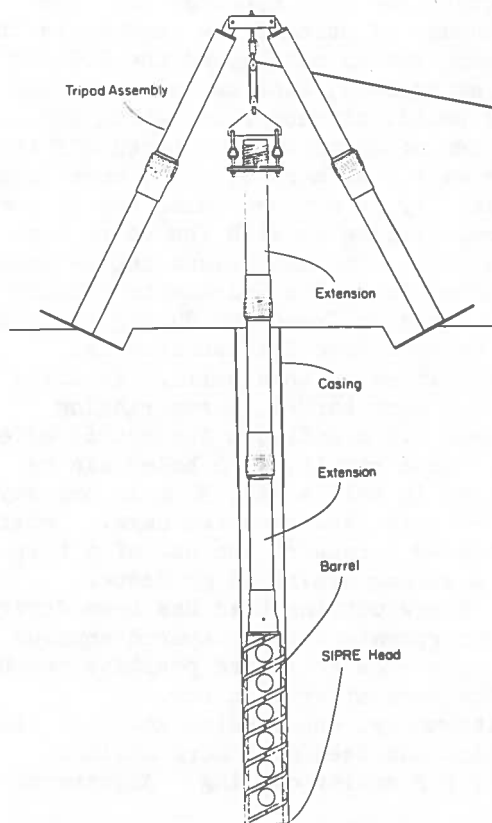


Figure 4. Lightweight auger with tripod assembly.

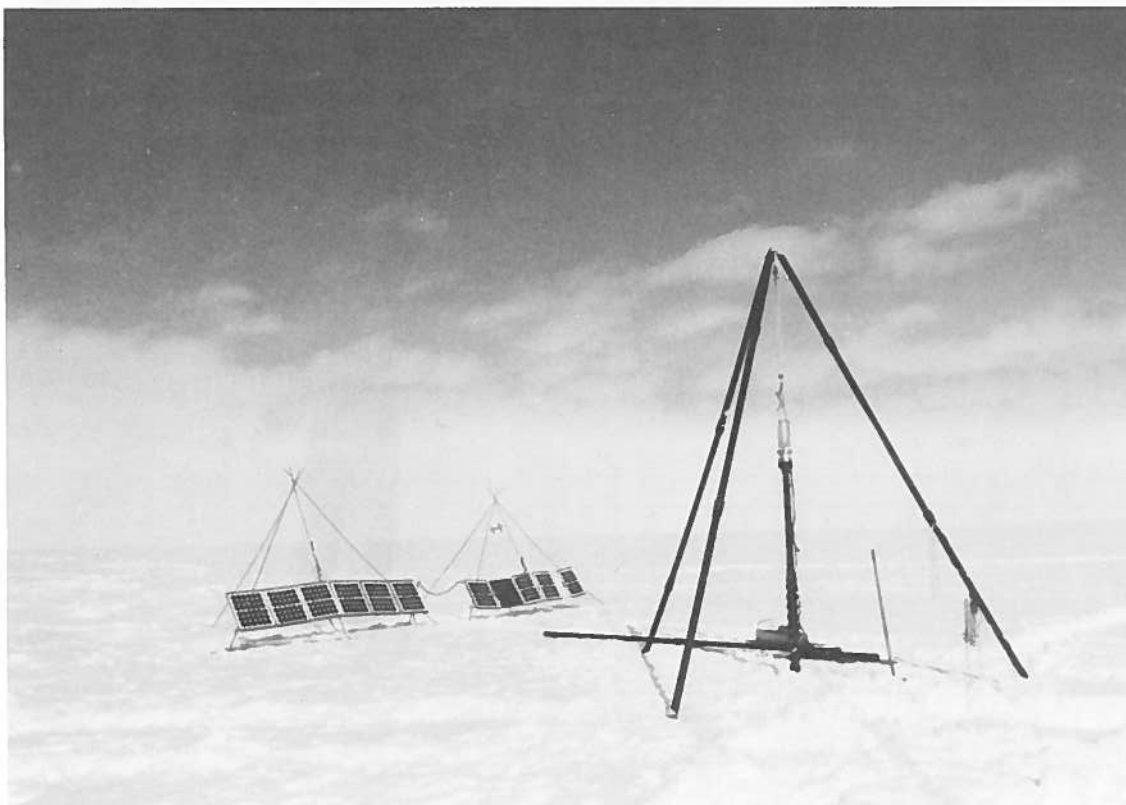


Figure 5. Lightweight auger with solar-generated power.

under contract DPP74-08414 with the
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ICE CORE DRILLING ON MT. WRANGELL, ALASKA 1982

Carl S. Benson Geophysical Institute
University of Alaska

ABSTRACT

Glacier ice in the summit caldera of Mt. Wrangell, Alaska (62°N; 144°W, 4000 m above sea level) has a mean annual temperature of about -20°C, an annual accumulation of 1 to 1.3 m water equivalent and thicknesses on the order of 500 m. In 1984 we plan to core through most of this ice using the Canadian modification of the Rufli-Rand drill. This project deals with a pilot project, done in 1982, using the PICO light weight drill which performed very well. We obtained 43.5 m of core which is being analyzed for microparticle content, total beta activity and stable isotope O^{18}/O^{16} ratios. The light weight was a major asset in transporting the drill by helicopter to the summit and in moving it by sledge on the surface. The drill was well designed and the versatile way that drill rods can be used to make a tripod proved useful. It was easy for one man to raise and lower the drill to depths of 30 m. At a depth of about 40 m the time required for an individual round-trip run to retrieve core was 45 minutes. Core lengths greater than 1 m were common when using the 2 m core barrel and core quality was excellent. Safe storage and shipment of the core proved to be more of a problem than the coring itself.

INTRODUCTION

In addition to the fact that widespread drilling in ice is a relatively recent activity, we recognize that most

of the ice core which has been obtained and analyzed is from the polar regions, primarily from the Antarctic and Greenland ice sheets, and the ice caps of Arctic Canada. This has provided valuable information on the properties of glacier ice itself, and historical information on paleoclimate and volcanic activity. There is an interest in examining ice core from other regions, including the equatorial parts of South America (Thompson et al., 1979) and Africa (Thompson, 1981). The present report deals with attempts to obtain ice core from the Alaska-Yukon glaciers on the northern rim of the Pacific Ocean. The first core from this region was obtained from the 5300 m level on Mt. Logan by G. Holdsworth in 1980 and is currently being analyzed. Holdsworth and the writer have selected the summit caldera of Mt. Wrangell, at the 4000 m level (Benson and Motyka, 1979) as the second site for ice core drilling in the Alaska-Yukon glacier system (Fig. 1). Ice thickness in the summit caldera of Mt. Wrangell is on the order of 500 m*; the core is intended to penetrate most of this ice in 1984 using Holdsworth's Canadian modification of the Rufli-Rand drill. The core from Mt. Wrangell will not only back up that from Mt. Logan; it

*Ice thickness determinations are based on radio echo sounding on the surface, by the writer with colleagues R. Motyka and the late P. MacKeith in 1976 and 1978, together with extensive airborne radio echo sounding done in collaboration with Dr. G. Clark, University of British Columbia during April, 1982.

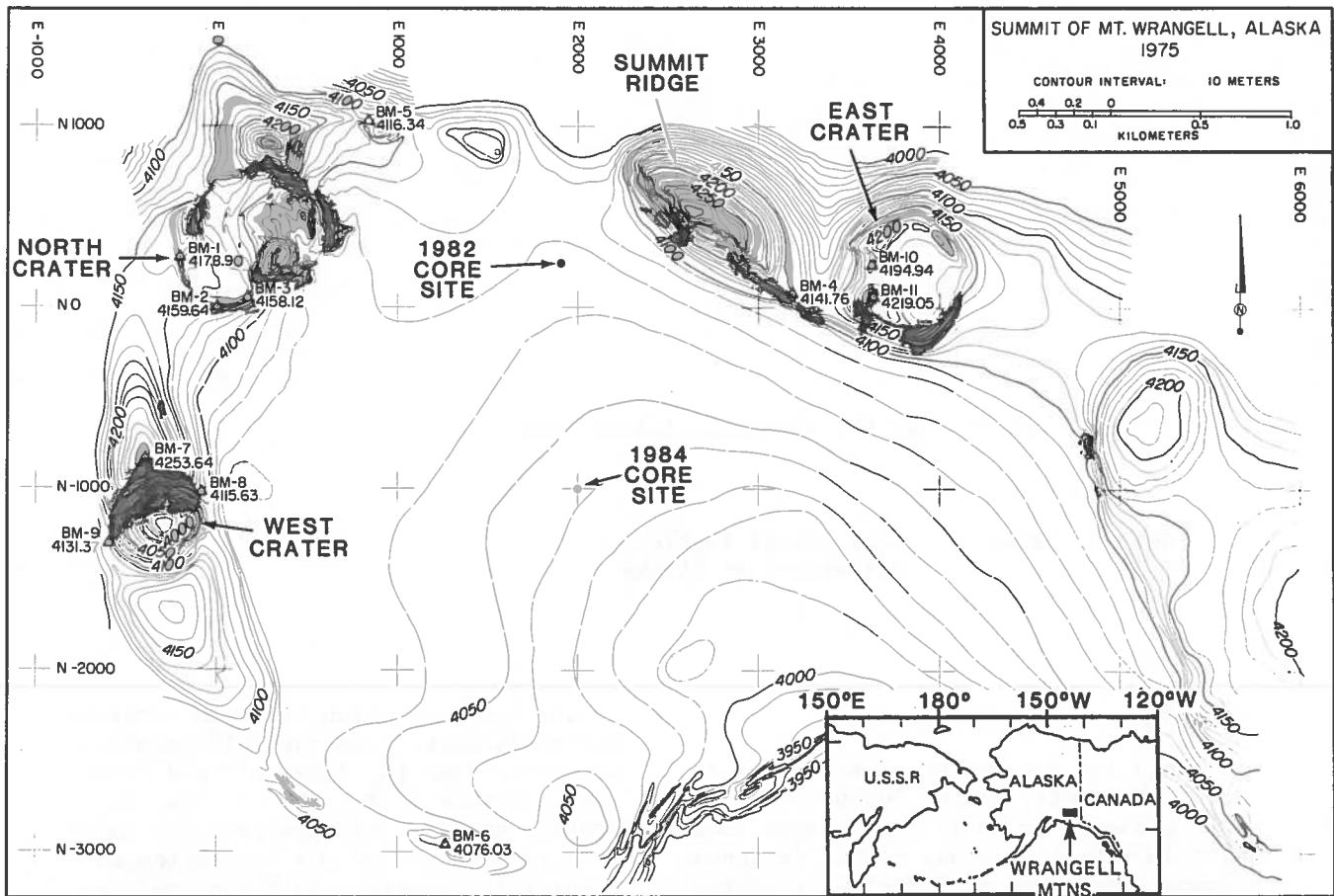


Figure 1. The summit of Mt. Wrangell based on aerial photographs taken in 1975. The broad summit has an area of about 35 km² above the 4000 m level. Dark areas on this map indicate snow-free areas. The North Crater has lost much of its ice cover since 1975. The 1982 core site was afflicted by sulfurous volcanic gases diffusing through the snow. The gases probably came from the fault zone lined with active fumaroles which arcs northwestward from BM-4 along the base of the summit ridge and under the snow about 300 m north of the 1982 core site. We expect that the proposed 1984 core site will be far enough from sources of volcanic gases to avoid the problems caused by gases diffusing through the snow. The aerial photography and mapping were done by North Pacific Aerial Surveys Inc. of Anchorage.

will also include more man-made contributions to air pollution, because it is from an altitude which is 1300 m lower.

In preparation for the 1984 ice coring project, a pilot project was done at the summit of Mt. Wrangell during 1982. The light weight core auger described by Koci (1984) was used; it was made available by the Polar Ice Coring Office (PICO), sponsored by the National Science Foundation, Division of Polar Programs. A total of 43.5 m of core was obtained and successfully transported to the Institute of Polar Studies (IPS), Ohio State University, Columbus, Ohio. Analysis of microparticles is being done by Drs. Ellen Mosley-Thompson and Lonnie Thompson; total beta decay is being measured by Dr. Ian Whillans, all of IPS. The core will be analyzed for δO^{18} in the Quaternary Research Center's

Laboratory at University of Washington, Seattle, Washington, by Drs. Pieter Grootes and Minze Stuiver. The results of these analyses will be interpreted together with results from pit studies and coring, to depths of up to 20 m, obtained in the 1960's and 1970's. This report deals with operational problems involved in obtaining ice core from Mt. Wrangell.

SITE SELECTION AND LOGISTICS

The drill site (Fig. 1) was selected away from the center of the caldera where previous studies (Benson, 1968; Benson et al., 1975) have shown accumulation to be a maximum, at about 1.3 m water equivalent per year. Accumulation at the drill site was expected to be on



Figure 5. The 2 m auger barrel being prepared for another trip down the hole. The light weight of the PICO drill made it easy for one man to handle. The usefulness of the ladder as a rack for drill rods is especially apparent in this view. The base of the summit ridge is seen on the left of center.

when coring nearly half of our man power and time went into logging, wrapping and storing the core.

The time required for making a round-trip run with the auger increased with depth of the hole. By the time we exceeded 35 meters it took 45 minutes to lower the auger, drill, pull it up and extract the core.

We used the 1-m long auger barrel in the first 10 m and then changed to the 2-m long barrel. The longer auger barrel proved very useful and core lengths of 80 to 130 cm were obtained. The quality of the core was excellent!

We did not use the core dogs on the PICO drill head. As a result the core sometimes protruded about 10 cm or more from the end of the auger when it was pulled out of the hole. However by carefully removing the auger we did not break the core as it was coming out of the casing and no core was lost. The

ends of the core varied from flat breaks, perpendicular to the cylinder axis, to spiral fractures. Spiral fractures complicate the core logging and the volume determinations required for calculation of density. The use of core dogs in the drill head may help in preventing spiral fractures.

The tripod, which is made from pieces of the drill rod, worked well. For the first 10 m or so it was not necessary when two people were drilling. But it proved to be very useful when only one person was drilling. The tripod blew down once and we laid it down or partially disassembled it when winds exceeded 25 knots. An aluminum ladder which was cached on the rim of the north crater from previous projects proved useful as a stand for the drill rod (Fig. 4 and 5).

During several warm days (-5°C or above) with clear skies, problems were

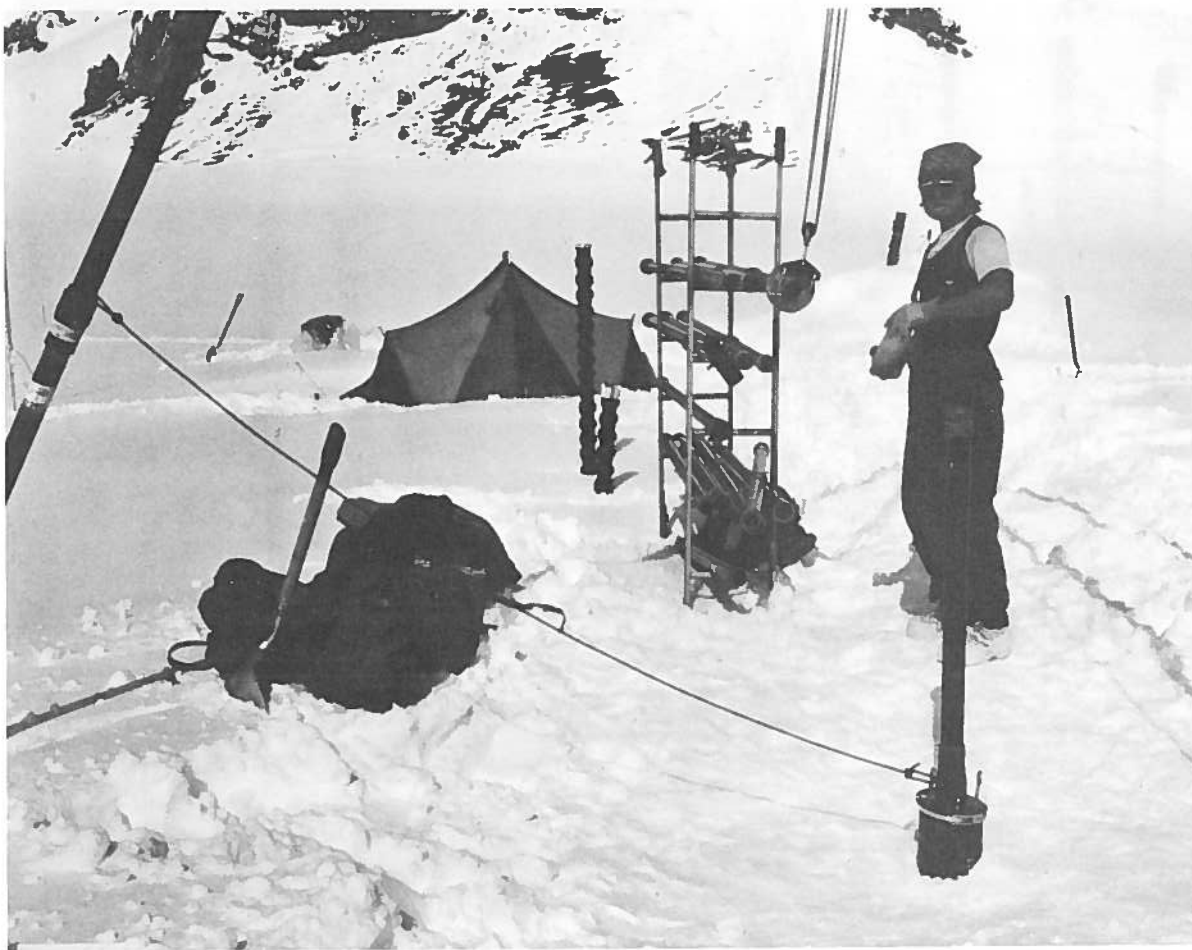


Figure 4. The 2 m auger barrel is shown being supported in the core hole by the support clamp on the casing, in order to protect it from direct solar radiation, while Dan prepares himself for the next drill run. The aluminum ladder, brought by helicopter from a cache on the rim of the North Crater, was very useful as a holder for drill rods.

fiberglass casing provided with the auger (Fig. 3 and 4). Most of the first 2 m of core was discarded because the upper snow layers were so weak that good core recovery was not possible. These strata were sampled in detail on the exposed pit wall; temperature was measured at 10 cm intervals as excavation proceeded; and samples were taken with 500 cm³ steel tubes inserted horizontally. The samples were weighed, so density values could be calculated, with a triple-beam balance which was sheltered from unstable air by being used in the bottom of the pit on the first day (29 June) that it was open. After being weighed they were sealed in plastic bags for laboratory analysis of microparticles. Another set of samples was taken for stable isotope measurements. The top of the logged core was determined to

be 194 cm below the snow surface of 5 July 1982. It was matched with strata which had been sampled in the pit.

The core drilling began on 5 July and ended on 17 July. However, storms made it impossible to drill during three of the twelve days and shut down operations for at least half of three other days. In addition to this direct loss of time to storms, there was a daily need to devote time to digging out from the effects of blowing snow. Of the nine days that we did drill and log core we averaged 4.6 m per day. The minimum was 2 m on 7 July when drilling was stopped by a major storm with winds from the east. The maximum was 9.1 m on 6 July. On five days we obtained 5 or more meters of core. Our rate could have been faster if we had not needed to devote so much time to survival and,



Figure 2. The 1982 core site with the puffing North Crater in background; the view is toward the west. The sun shield which served as protection for the core while it was being logged is to the left of the tripod. In front of our tent is a solar snow melter designed by Solie and Sturm; on bright sunny days it provided up to 9 liters of water.



Figure 3. Dan Solie cleaning the 1 m auger barrel which was used to start the core, the 2 m auger was used below 10 m. A piece of core can be seen in the core logging holder. In this photo two of the insulated boxes used to store and ship the core were being used as a platform for core logging. Before core was put in the boxes they were buried or placed in the pit bottom to maintain their temperatures at -12°C and away from solar radiation. The casing in the top of the core hole can be seen in the left center, near the mittens. To the left of the tent is the snow drift that we built in our "gased out" attempt to make an igloo (see text). The base of the summit ridge with its active fumaroles is in the background.

the order of 1 m water equivalent per year. We planned to drill on the caldera side of the divide where a small amount of ice exits from the north rim of the caldera.

The light weight of the drill was a major advantage. It fit into five zipper-locked bags and was transported to the summit together with other equipment by a modified Bell 47 helicopter; the modification included replacement of the piston engine with a jet engine and installation of a larger tail rotor (the Solyo conversion). Air transport was from the Gulkana airstrip, or from Copper Center, both of which lie 75 km west of the summit of Mt. Wrangell. A staging area was established on the Chetaslina Glacier which is on the west flank, 6 km west of, and 2000 m below, the summit. Five helicopter trips, one of which carried a large sling-load, were required from the staging area to establish the summit camp. Originally we planned on having a four man team at the summit. Following nearly a month of field work on the Chetaslina Glacier, two of us (D. Solie and C. Benson) were transported by helicopter from the west flank directly to the summit caldera. The other two (M. Sturm and C. Tobin) planned to climb to the summit after completing a series of measurements on the Chetaslina Glacier. The first two people on the summit planned to establish a camp, complete a snow pit study to 3 to 4 m depth and initiate drilling from the pit floor while the climbing team ascended the west slope, doing shallow pit studies en route. The pit was to be covered with a tarp supported by a framework of timbers to prevent it from being filled by blowing snow. We have had experience with drilling from the bottom of pits in Greenland and on Mt. Wrangell and expected this plan to enable us to work in any weather. We also have had enough experience with storms on Mt. Wrangell to know that special provisions for bad weather were essential for efficient operation. Unfortunately, two problems modified our plans. First, the climbing team did not reach the summit--it had to be evacuated by helicopter from the west flank because of a dental infection. Thus, the summit operation was reduced to a two-man effort, and some of the projects originally planned had to be abandoned. The second problem arose because sulfurous volcanic gases diffused through the snow and filled the pit making it impossible to inhabit when it was covered.

Most equipment had been transported to the summit on 12 June while volcanic gases of the North Crater (Fig. 2) were being sampled by Roman Motyka (of Alaska Division of Geological and Geophysical Surveys) and Matthew Sturm. When we arrived at the summit with camp gear on 27 June, we found the helicopter sling load had touched down too close to the divide so we spent our first two days establishing a camp and sledging things to the drill site marked on Figure 1.

The pit study was begun on 29 June and completed to a depth of 2.10 m before we covered it to prevent it from being filled overnight by blowing snow. When we uncovered the pit enough to enter it on 30 June we found it full of sulfurous volcanic gases that had diffused through the snow and settled in the pit. Because of stormy weather with blowing snow it was not possible to leave the pit uncovered, and the volcanic gases made it impossible to continue excavation and sampling in the covered pit as we had originally planned to do. Therefore, we decided to leave the pit covered as a place to store the core but to abandon our plan of drilling from its bottom and to drill from the surface instead.

The pervasiveness of the gases diffusing through the snow was illustrated in several other ways. Once the coring was underway we could smell the fumes coming out of the core hole. Surprisingly, gases diffusing through the snow also cancelled our plans for building emergency shelters. Because of the potential for severe storms at the summit we planned to make snow caves and igloos to live in. To make such a "home" we built a large drift by piling snow near our tent and equipment cache (Fig. 2 and 3) but, when we dug into it to make an igloo we found volcanic gases filled any excavated volume within the snow. Thus, we were obliged to live on the surface in a tent as well as doing the drilling and core logging on the surface. This meant that we could not weigh the core pieces as they were logged because the triple-beam balance needed complete protection from wind. Wind and blowing snow closed down our entire coring operation when winds exceeded 25 knots.

CORE DRILLING

The core hole was located 5 m from the test wall of the pit. The top meter of the core hole was cased with the

caused by the strong solar radiation. It was necessary to shade the core to prevent it from warming while it was being logged and cut on the snow surface (Fig. 2). Most troublesome was the partial melting of cuttings on the drill barrel and cutting head when they absorbed solar radiation. Since the temperature in the core hole was about -20°C , any droplets or wet snow quickly froze and interfered with the drill's cutting action. We dealt with the problem by removing the core as quickly as possible and immediately putting the drill barrel back into the hole. The tripod made this operation possible because the drill barrel could be supported in the hole, as shown in Figure 4, while preparations were made for the next drill run. The black plastic material used to make the spiral flights on the outside of the barrel was an especially efficient absorber of solar radiation. If white rather than black is available for the drill flights it may help prevent melting on the drill barrel when it is unavoidably exposed to direct solar radiation.

Two acute problems arose. The first was when a drill bit broke while drilling at the 9 meter depth. The break occurred where the mounting screw holds the bit onto the drill head. The hole for the mounting screw was counter sunk so deep that the amount of metal holding the screw head was about 1 mm thick (see Koci, 1984, Fig. 3). The broken drill bit was recovered from the hole by drilling very carefully and pulling the drill up slowly during the next drill run. The second problem occurred when the drill got stuck 40 m below the surface. Efforts to break it loose by twisting were unsuccessful. It was freed by jerking repeatedly in the vertical direction. More than an hour was spent extricating the drill. During our efforts to free the drill, the threaded junctions became very tightly joined, and wrenches had to be used with extension bars to unscrew each junction.

We experimented with a two-speed (300 and 1200 rpm) electric power drill which had been modified for use with the SIPRE auger. Power was supplied by a portable generator which was also used to run an electric chain saw in the pit work. The drill worked smoothly, but even though we used the slow speed it was so fast that we could not easily tell when the core barrel was full and we were apprehensive about getting the drill stuck. The drill also had a fault-

ty switch that prevented more extensive use of it. However, because the time spent drilling was so much less than the time raising and lowering the drill pipe, especially at depths greater than 20 meters, and because the logistics of using the generator were complex we probably would choose to go without the electric power in order to reduce weight and space of the field experiment for a pilot study. However, if extensive coring was to be done, i.e., multiple holes in a region with adequate transportation, it would be worthwhile to devote time to developing the electric drill.

STORAGE AND TRANSPORT OF THE CORE

Our goal was to keep the core at temperatures below -10°C from the time it was removed from the coring auger until it was safely in cold storage at the Institute for Polar Studies in Columbus, Ohio. Although mean annual temperature is -20°C at the summit of Mt. Wrangell and the snow surface temperature rarely reaches 0°C , it was necessary to protect the core from direct solar radiation and, in one case, from surface air temperatures of near 0°C which were experienced during a storm on 7 July.

When the core was removed from the auger it was placed on a holding platform with its top indicated. It was measured, cut and logged piece-by-piece with notes made on grain size, core quality, ice lenses and glands - and, in rare cases, visible sediment was observed and noted. The core was then inserted into polyethylene sleeves and a card describing each core was enclosed before the sleeve was stapled shut. The wrapped core was stored in "Thermosafe" insulated containers* (Fig. 3) which were kept buried or stored in the pit at temperatures below -12°C . Dry ice (solid CO_2) purchased in Fairbanks, trucked

*The boxes were purchased from Polyfoam Packers Corp., 6415 N. California Ave., Chicago, Illinois 60645. We used Thermosafe Utility Insulated Container, Model No. 305, insulation wall thickness 2-1/2 inches (6.4 cm), capacity 5 ft³ (0.14 m³), with internal dimensions of 23 x 14 x 23 inches (58.4 x 35.6 x 58.4 cm). The seamless, molded containers are made of expanded polystyrene (0.19 K factor); the exterior surface is protected by a tough laminated fiberboard case. Nylon webbing provided closure and carrying straps.

to Glennallen, and brought to the summit by helicopter was packed with the core in each of the three boxes; they were transported from the summit to the staging area on the Chetaslina Glacier in a single sling load. As soon as everything was off the summit, the core was flown 75 km to Copper Center. It was then taken 30 km by truck to a freezer in Park's Grocery in Glennallen and stored by courtesy of the owner Park Krine. After two days it went by pickup truck across 400 km of "rural" Alaska to Fairbanks where it arrived in excellent condition even though the dry ice had evaporated en route. In Fairbanks the core was stored for 6 days in the freezer of Aurora Meat and Seafood, by courtesy of Mr. Josef Schruf. When the complex shipping arrangements were completed, the three core boxes were repacked with dry ice and sent by commercial air freight for nearly 6000 km, across five time zones, from Fairbanks, Alaska to Columbus, Ohio. Potential delays were feared at several points along the route, but Murphy's Law was apparently suspended until the three boxes of core arrived, in excellent condition, at Columbus with dry ice remaining in each box. In Columbus, Dr. E. Mosley-Thompson felt that the core could have survive another day's delay enroute without its temperature exceeding -10°C .

In summary the PICO light weight drill worked very well. Safe storage and shipment of the core proved to be more of a problem than the coring itself.

ACKNOWLEDGEMENTS

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ANTITORQUE LEAF SPRINGS

a design guide for ice-drill antitorque leaf springs

by

N.Reeh
Geophysical Isotope Laboratory
University of Copenhagen
Haraldsgade 6
DK-2200 Copenhagen N
Denmark

Abstract: By shaping the leaf spring according to a fourth order parabola, a uniform load distribution is obtained along the line of contact with the ice. For this leaf spring geometry, the radial load, the supporting force and the maximum bending moment in the spring are calculated.

Introduction

The leaf spring antitorque device is an improvement over most other designs, due to the following qualities:

- Mechanically, it is very simple consisting of three pre-bent leaf springs, each supported at the ends by hinges.
- The rise of the springs and thereby the pressure exerted on the hole wall, may easily be adjusted by changing the distance between the hinges.
- The springs are flexible, allowing easy passage of e.g. ice layers or other irregularities at the wall of the drill hole.

The method of rational design of antitorque leaf springs presented here, was developed for the Danish light-weight drill (Johnsen, 1980). Experience with this drill and the Danish deep drill (Gundestrup, 1982) has led to a satisfactory design procedure.

Leaf spring geometry

Figure 1 shows a sketch of the spring. In the figure,

- r = radius of the hole,
- $b + e$ = radial distance of the spring supports (hinges) from the hole wall,
- e = eccentricity,
- $2k$ = distance between the spring supports (assumed to be fixed).

The undeformed spring consists of three sections: two rectilinear ones adjacent to the supports of length c (projected length a , see figure 1), and a curved section with chord length $2l$ and rise f_1 (thick full curve in fig.1).

The calculations are simplified, if the two points of transition between the spring sections (points C and D in figure 1) coincide with the hypothetical points of intersection between the undeflected spring and the hole wall. We assume this to be the case. The total rise of the spring will accordingly be $f_1 + b$.

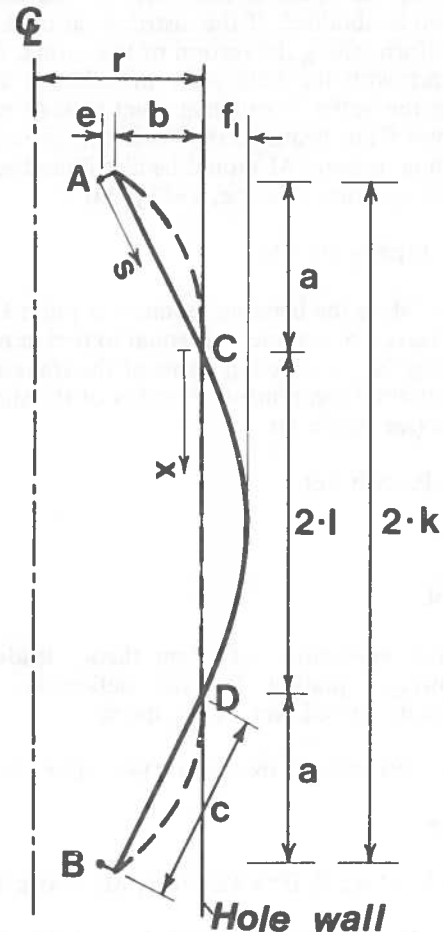


Figure 1. Leaf spring geometry

When the spring is deflected by being pressed against the hole wall, the curved section is straightened out and the rectilinear sections are bent (thick broken line in figure 1). The transition points C and D will be displaced a short distance along the hole wall in the direction towards the supports. Assuming the ratio $f_1/(2l) \ll 1$, the displacements are insignificant and are consequently ignored. This means, that the section of the deflected spring contacting the wall is assumed to have the length $2l$, and that the chord lengths of the curved sections of the deflected spring are equal to c .

Design principles and equations

The following rules are used in the design of the leaf springs:

1. The load distribution should be uniform along the section of the deflected spring, that is in contact with the wall.
2. The transitions between the curved and rectilinear sections of the spring should be smooth, both in the deflected and undeflected states.
3. The length of the spring is preserved during deflection.
4. The deflections are calculated using ordinary beam theory.

The highest rotation resistance of the antitorque system is obtained, if the distribution of the load p is uniform along the section of the spring, that is in contact with the hole wall. Introducing an x -axis along the wall with origin at point C (see figure 1), it follows from beam theory, that the corresponding bending moment M should be distributed according to the equation (Hartog, 1949 p.34)

$$M = -\frac{1}{2}px^2 + plx + M_c, \quad (1)$$

where M_c is the bending moment at point C (which for reasons of symmetry is equal to that at point D). M_c may be expressed in terms of the transverse and longitudinal components P and N of the supporting force (see figure 1):

$$M_c = Pa - N(b + e), \quad (2)$$

where

$$P = pl. \quad (3)$$

Further application of beam theory leads to the following equation for the deflections of the originally curved part of the spring

$$f/k = \gamma^3 P^* (1/24x^{*4} - 1/6x^{*3} + 1/3x^{*2}) + \gamma^2 M_c^* (x^* - 1/2x^{*2}), \quad (4)$$

where

$$\gamma = 1/k, \quad x^* = x/l, \quad P^* = Pk^2/(EI), \quad M_c^* = M_c k/(EI),$$

E = Youngs Modulu and $I = 1/12wt^3$ is the

moment of inertia of the spring cross section (w = width and t = thickness).

The expression for small deflections of a straight beam has been applied, even though the actual deflections are not small and the undeflected 'beam' is not straight. However application of a more correct - and correspondingly more complicated - theory is not likely to change the results significantly.

Eq. (4) ensures, that the deflections of points C and D are zero, in accordance with a previous assumption. Since section CD is deflected into a straight line, the shape of the curved central section of the undeflected spring is exactly given by eq. (4).

To ensure a smooth transition between the curved and the rectilinear sections of the undeflected spring, the slope of the curved spring section df/dx at points C and D should be equal to $\pm b/a$.

This imposes the following condition on P and M_c :

$$M_c^* = b^* / [\gamma(1-\gamma)] - 1/3 \gamma P^*, \quad (5)$$

where $b^* = b/k$, and P^* , M_c^* and γ have been given above. Combining eqs. (2) and (5), yields

$$N^* = P^* (1 - 2/3 \gamma) / (b^* + e^*) - b^* / [(b^* + e^*) \gamma (1 - \gamma)], \quad (6)$$

where

$$N^* = Nk^2/(EI) \text{ and } e^* = e/k.$$

Next consider section AC, along which an s -axis is introduced with origin at point A.

According to the theory of a beam subject to normal forces, the differential equation for the deflections of section AC will read (Hartog, 1949, pp.188-189)

$$EI d^2 f/ds^2 + f(Pb/c + Na/c) = Ne - (M_c + Ne)s/c,$$

which has the solution

$$f/k = f_s \sin(\omega s/c) + f_c \cos(\omega s/c) + a_0 + a_1 s/c, \quad (7)$$

where

$$\omega^2 = [P^* b^* + N^* (1 - \gamma)] \sqrt{(1 - \gamma)^2 + b^{*2}}, \quad (8)$$

$$a_0 = N^* e^* \{ \omega / [P^* b^* + N^* (1 - \gamma)] \}^2, \quad (9)$$

$$a_1 = -(M_c^* + N^* e^*) \{ \omega / [P^* b^* + N^* (1 - \gamma)] \}^2, \quad (10)$$

$$f_c = -a_0, \quad (11)$$

$$f_s = -(a_1 + a_0) / \sin(\omega) + a_0 \cos(\omega), \quad (12)$$

Assuming k , b and e to be known, it appears that the deflection curve eq. (7) is dependent on the unknown quantities γ , P^* , N^* and M_c^* . However, through eqs. (5) and (6), the number of unknowns may be reduced to two, e.g. γ and P^* . In order to determine these unknowns, two additional

equations must be set up: One expressing, that the slope of the deflection curve given by eq. (7) equals $b^*/(1-\gamma)$ for $s = c$, the other expressing that the length of the spring is preserved. The two equations read:

$$\omega f_s \cos(\omega) - \omega f_c \sin(\omega) + a_1 - b^*/(1-\gamma)\sqrt{(1-\gamma)^2 + b^{*2}} = 0, \quad (13)$$

and

$$\int_0^c \sqrt{1 + (df/ds)^2} ds + 1 = \int_0^1 \sqrt{1 + (df/dx)^2} dx + c, \quad (14)$$

Equations (13) and (14) are two transcendental equations in γ and P^* , that must be solved by numerical methods. The solutions are shown in figure 2 a and b for various values of the dimensionless parameters b/k and e/k .

In figure 2 are also plotted additional quantities, that are useful in the leaf spring design. A practical design schema is given below.

The main characteristic lengths k , b and e of the leaf spring geometry are constrained by practical considerations. Next the dimensionless force N^* and the maximum bending moment M_s^* which occurs near the midpoint of section AC, are obtained from the diagrams shown in figure 2c) and d) and the maximum allowable thickness of the spring is calculated from the expression

$$\sigma_b/E = 1/12(t/k)^2 N^* + 1/2(t/k) M_s^*, \quad (15)$$

where σ_b is the allowable bending stress of the spring material. In most practical cases t/k is of magnitude 1/100 and the N^* -term is negligible. In this case the maximum allowable thickness of the spring is given by the simplified expression

$$t = 2k\sigma_b/(EM_s^*), \quad (16)$$

The value of P^* can now be found from the diagram shown in figure 2a, and the total radial force exerted by the antitorque system on the hole wall can be calculated as (assuming 3 springs):

$$P_r = 1/2 P^* E w t^3 / k^2, \quad (17)$$

If the approximate thickness given by eq. (16) is introduced, we get

$$P_r = 4k w \sigma_b^3 P^* / (E^2 M_s^{*3}),$$

If this force - with a reasonable choice of the spring width w - is sufficient to prevent the drill from rotating, the next step will be to obtain γ from the diagram shown in figure 2b. Then l and a can be calculated, $l = \gamma k$ and $a = (1-\gamma)k$ respectively. Finally the shape of the curved section of the spring can be obtained by means of eq. (4), using the values of γ and P^* found above, and the value of M_c^* obtained from the diagram shown in figure 2e. The rise of the curved spring section can be found from figure 2f.

If the radial force given by equation (17) is too

small, different characteristic lengths k , b and e should be used, and the design procedure repeated until a satisfactory result is obtained.

The spring supports of course should be designed to carry the combined loads N and P .

Example

For the Danish ISTUK deep drill (Gundestrup, 1982) the characteristic lengths of the antitorque system are $k = 34.5$ cm, $b = 3.7$ cm and $e = 0.6$ cm, resulting in $b/k = 0.107$ and $e/k = 0.0174$.

With these values, the following dimensionless quantities are obtained from the diagrams shown in figure 2: $P^* = 4.25$, $\gamma = 1/k = 0.452$, $N^* = 20.4$, $M_s^* = -0.97$, $M_c^* = -0.208$, and $f_1/k = 0.060$.

Taking $w = 2$ cm, $t = 0.25$ cm and $E = 2.1 \cdot 10^6$ kp/cm², the corresponding non-dimensionless quantities become: $P = 19.5$ kp, $l = 15.6$ cm, $a = k - l = 18.9$ cm, $N = 93.7$ kp, $\sigma = 7580$ kp/cm² (eq.(15)), and $f_1 = 2.1$ cm.

Finally the shape of the curved section of the spring is found by means of eq.(4). The following table presents the results:

x/l	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
f (cm)	0	0.31	0.62	0.92	1.20	1.46	1.67	1.85	1.98	2.06	2.08

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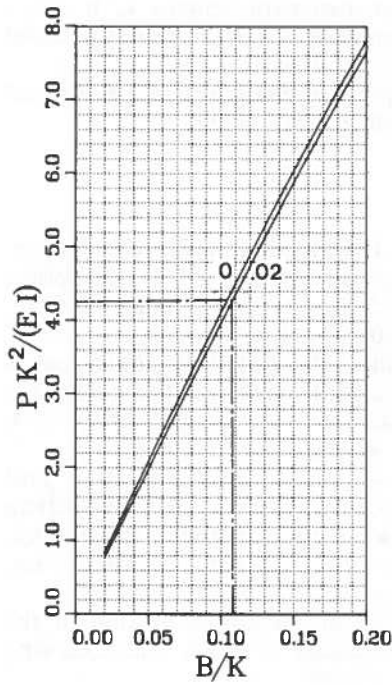


Figure 2a. Dimensionless transverse supporting force as function of b/k for the indicated values of the dimensionless eccentricity of the spring support.

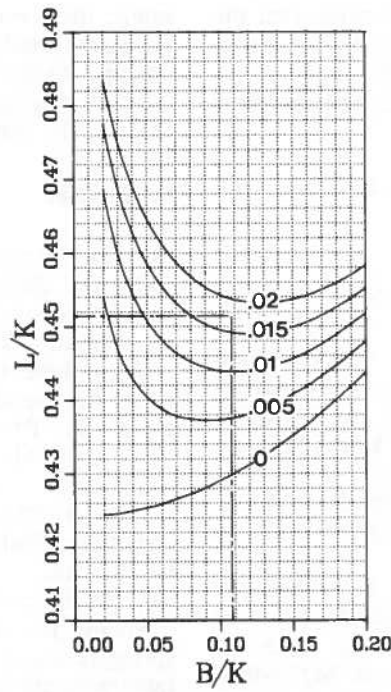


Figure 2b. Chord length of curved spring section as function of b/k for the indicated values of the dimensionless eccentricity of the spring support.

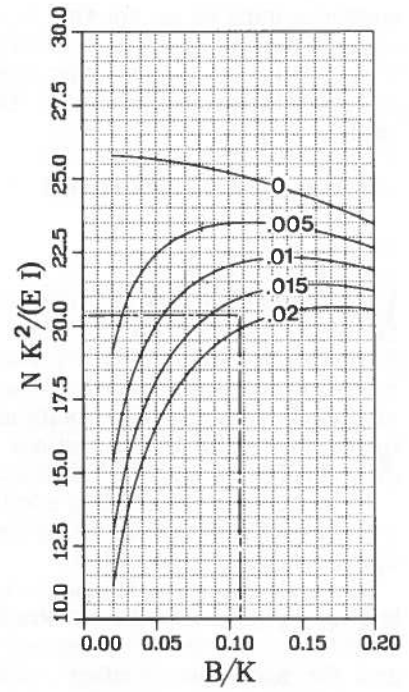


Figure 2c. Longitudinal supporting force as function of b/k for the indicated values of the dimensionless eccentricity of the spring support.

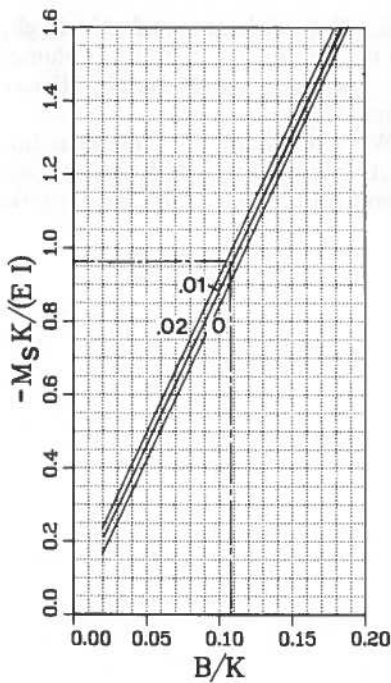


Figure 2d. Maximum absolute bending moment as function of b/k for the indicated values of the dimensionless eccentricity of the spring support.

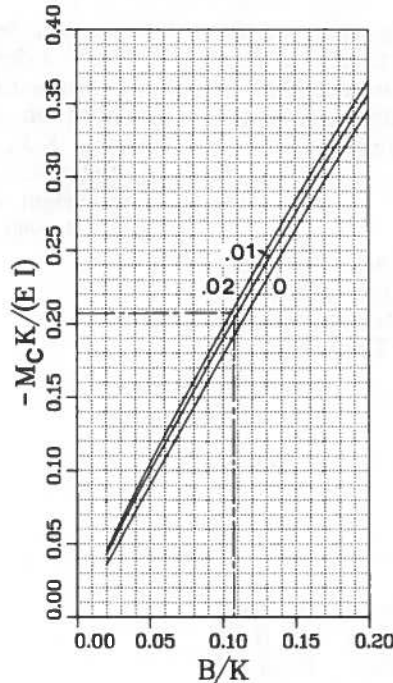


Figure 2e. Bending moment at transition point as function of b/k for the indicated values of the dimensionless eccentricity of the spring support.

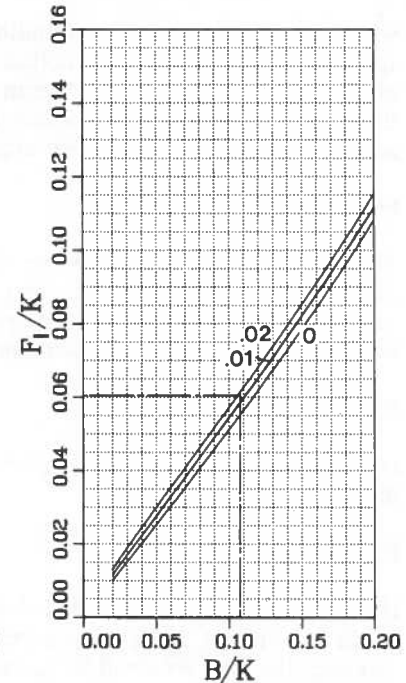


Figure 2f. Rise of curved spring section as function of b/k for the indicated values of the dimensionless eccentricity of the spring support.

Figure 2. Leaf spring design diagrams.

ICE CORE QUALITY IN ELECTRO-MECHANICAL DRILLING

F. Gillet, D. Donnou, C. Girard, A. Manouvrier, C. Rado and G. Ricou
Laboratoire de Glaciologie et Geophysique de l'Environnement, C.N.R.S., Grenoble, France

ABSTRACT

Using an electro-mechanical drill working on the principle developed by J. Rand and H. Rufli, four holes have been drilled in different locations. In each of these drillings it has been observed that the core quality was excellent in the firn, but in the ice, fractures appeared. Certain pieces of core were highly broken and sometimes core was completely sliced into irregular discs 1 or 2 cm thick.

After a brief description of the drill, we describe the main phenomena observed and we attempt to determine the possible causes of the fracturing.

INTRODUCTION

In 1976-77, with the help of information given by J. Rand and H. Rufli, we built an electro-mechanical drill based on design features of the two drills previously developed.

Four holes have been drilled with this equipment as follows:

Site of core	year(s) 19--	Depth (m)	Temp °C	Firn to ice (m)
Dome C (I)	77/78	140	-53	100
Dome C (II)	78/79	180	-53	100
Adelie Land D57	80/81	203	-32	80
James Ross Is.	1981	150	-14	70

During these four operations, we never had problems with sticking of the drill in the hole. However, in connection with the core catchers, we occasionally had some difficulties recovering the cores. Sometimes it was difficult to penetrate the ice. The main problem encountered concerned the quality of the cores. For all drillings, this quality was excellent in the firn but deteriorated on arriving at the firn/ice transition. It is important to try to understand the reasons for this: the aim of this paper is to determine the main factors which may have an effect upon this phenomenon.

EQUIPMENT

The drill unit is 4.20 m long and weighs 120 Kg. The hole that is bored is 14.3 to 14.4 cm in diameter and the core retrieved has a diameter of 9.9 to 10 cm. The drill is comprised of three main sections:

The Anti-torque Section

This section of length 1.10 m is equipped with four 0.72 m long steel springs working in the same way as J. Rand's unit (Rand, 1976). A slipping assembly avoids any twisting of the cable if the anti-torque device rotates. An 11 Kg lead weight, having a 17 cm axial movement, helps to break the core by shock impact or to recover the drill if it is slightly stuck at the bottom of the hole.

The Motor Reducer Section

This section of length 0.80 m consists of a 3 phase, 380 V, 1.5 HP submersible AC motor connected to the gear reducer (ratio 1:27) which is mounted in a tube filled with oil. The oil is used for lubrication and also for heat dissipation. The shaft going to the core barrel rotates at a speed of 105 RPM. It is constrained by two bearings (Rufli, 1976) to limit the vibrations which can occur in the upper part of the barrel (Fig. 1).

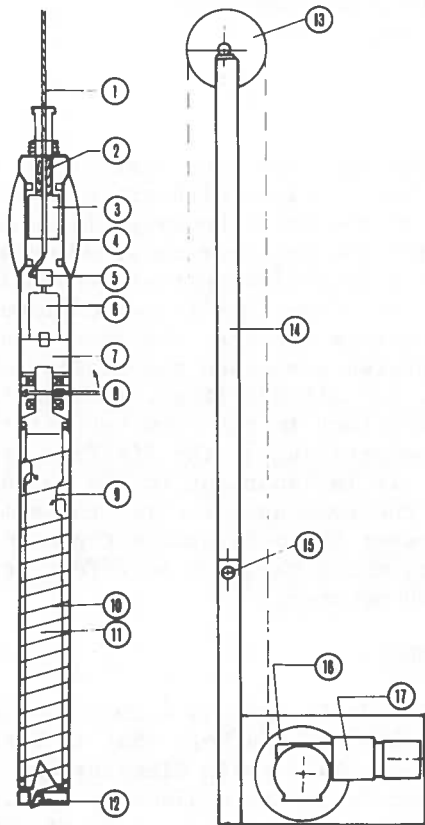


Figure 1. Schematic diagram of the drill, tower and winch assembly. (1) Electro-mechanical cable. (2) Cable termination. (3) Knocker weight. (4) Spring. (5) Slip-ring. (6) Submersible motor. (7) Gear reducer. (8) Clutch. (9) Chip inlets. (10) Auger flights. (11) Core barrel. (12) Cutters. (13) Sheave. (14) Mast. (15) Rotation axis of mast sections. (16) Cable drum. (17) Hydraulic motor reducer.

The Core Barrel Section

The core barrel of length 2.3 m has an outer jacket made from a stainless steel tube, 14 cm OD with a 2 mm wall thickness. Three steel strips (1.5 mm thick) are fixed inside the jacket to provide a better movement of the chips on their way up the flights. The inner barrel is a steel tube 10.8 cm OD with a 2 mm wall thickness. Two different types of inner barrel have been used. The first, used at Dome C, was used with the same two cutters and core catching system as used in the SIPRE hand auger. The two lead auger flights, made of polyethylene, have a pitch of 15 cm. The second has three round cutters (Fig. 2) and three core breakers which are tripped against the core by giving a small reverse rotation to the motor.

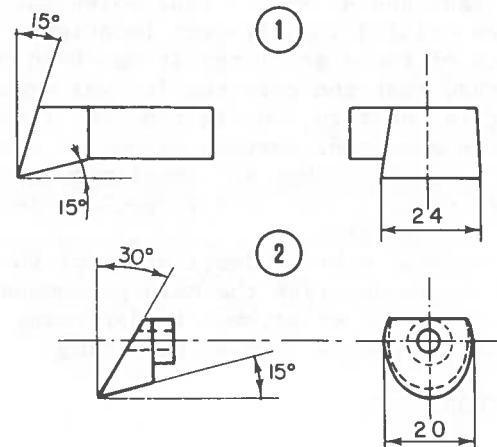


Figure 2. Cutter design. (1) Electro-mechanical drill No. I used at Dome C. (2) Electro-mechanical drill No. II used at site D57 and James Ross Island. (Dimensions are in mm).

The polyethylene spirals have now been replaced by stainless steel ones, which, being thinner, increases the space available to the chips. Corresponding to the three cutters, there are three auger flights with a pitch of 15 cm.

DESCRIPTION OF THE PHENOMENA OBSERVED AT THE FOUR DRILLING SITES

Dome C (I)

The density curve (Fig. 3) shows that the limit of the firn can be estimated to be at about 100 m depth. This depth was confirmed by other measurements made to determine the depth of the pore close-off. In the firn, the quality of cores was very good. The first broken cores appeared at 88 m, then at 90 m, 101 m, 105 m and 120 m. At 127 m the number of broken cores increased slightly until 138 m. Then, suddenly, all cores showed fractures in different places. As the electro-mechanical drill was just used for starting the hole for the thermal drill, we did not go deeper than 140 m with this equipment.

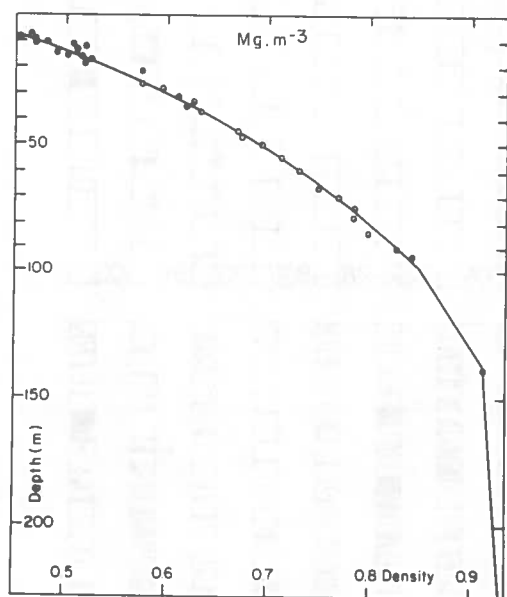


Figure 3. Density as a function of depth at Dome C.

Dome C (II)

The first broken cores appeared at 114 m, much later than at Dome C (I). At 115 m, the cutter shape was modified in order to increase the diameter of the cores in an attempt to make their retrieval easier. Then, until 126 m, 9 cores of 19 were partially broken. From this depth down, all the cores showed fractures, half of them being heavily broken. At 137 m, we increased the internal clearance of the cutters, in an attempt to restore them to their initial shape. We observed immediately, an increase in the quality of the cores, and, until 160 m, about 65 % of them were good. Beyond 160 m depth, almost all cores showed fractures, 30 % of them being heavily or totally broken. The most frequent frac-

ture shape was a type of slicing into small irregular discs having a thickness of 1 or 2 cm.

Concerning the partially broken cores, we would notice that it was often the upper part of them that was most fractured.

Site D 57

Referring to the depth-density curve (Fig. 4), the limit of the firn can be estimated to be at about 80 m depth.

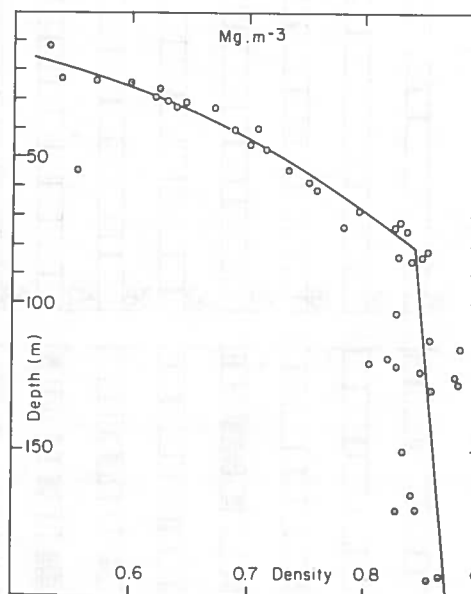


Figure 4. Density as a function of depth at Site D 57.

The first fractures appeared at 98 m and 100 m, where, respectively, 3 cm and 11 cm of the lower part of the cores were broken. Also, a few fractures in the ice were visible at the bottom of some cores. This could probably be explained by the action of the core breakers. More significant fractures appeared at 112 m depth. Their number increased with depth.

From 98 m until 203 m the total length of broken core is 13.4 m which represents 13 % of the total.

The logging of the core, carried out by M. Creseveur, enabled Figure 5 to be prepared. The main results are summarized in Table 1.

James Ross Island Site

The density curve (Fig. 6) gives a

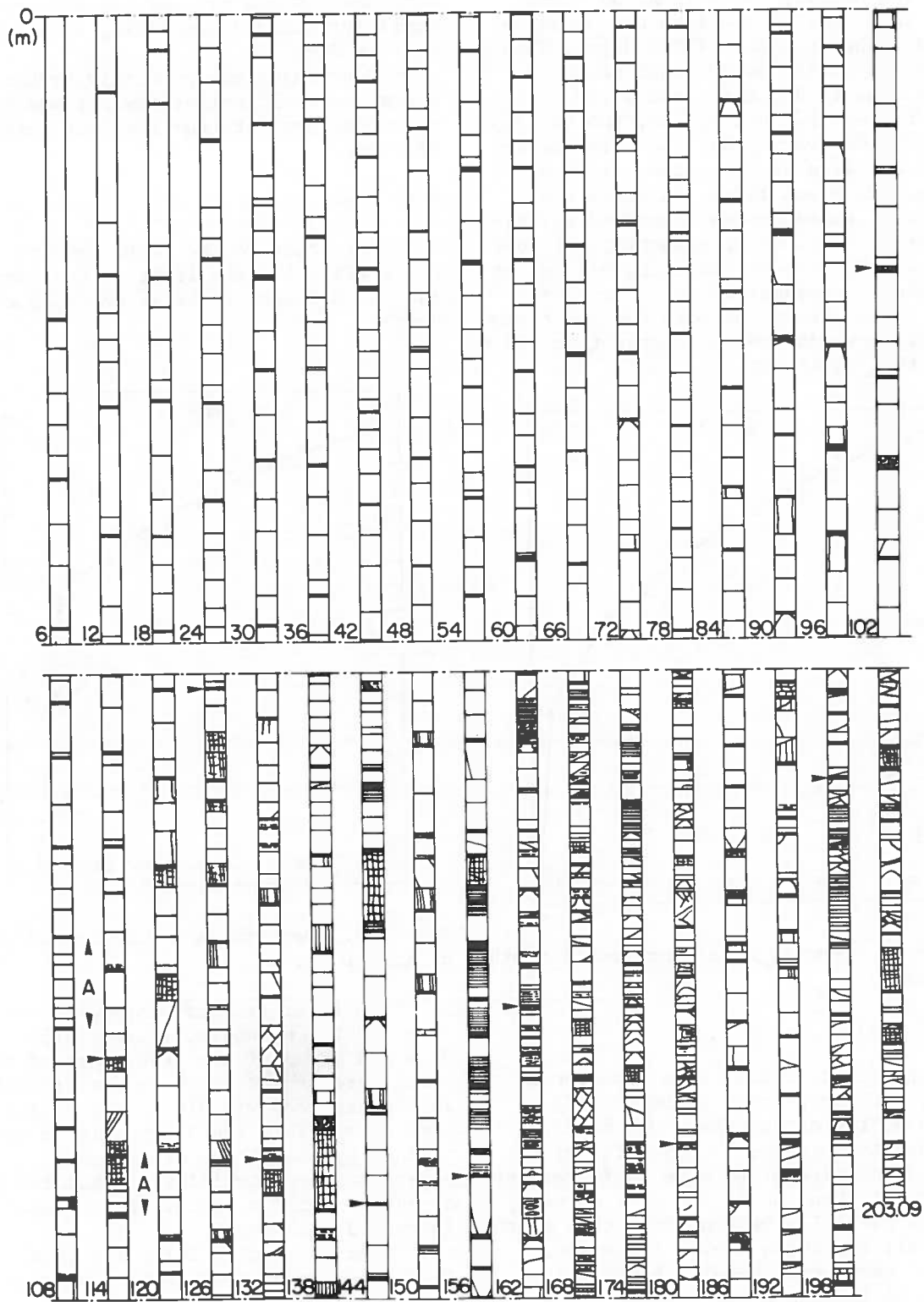


Figure 5. Core logging information at Site D 57, showing the different core fractures observed in the ice. The thick horizontal lines correspond to the limit of the cores obtained in each run. The symbol "A" indicates runs made with the core barrel used at Dome C (No. I).

TABLE 1

Depth (m)	Length of broken core (%)	Average length of core segments (cm)	Comments
0 - 98	0	29	Very good quality core
98-112	1.5	26	
112-120	11.0	22	
120-131	18.0	17	
131-143	24.0	17	Of the 24%, 14% were totally broken
143-152	7.0	21	At 143 m the clearance angle was reduced
152-155	53.0	1 - 2	Heavily broken into small discs
155-160	13.0	9	
160-179	13.0	6 - 8	Moderately broken into short sections
179-193	3.0	15 - 16	Cutters modified at 178.54 m
193-203	17.0	6 - 8	Core quality deteriorating in spite of frequent cutter sharpening. Chip transport is difficult.
Total depth reached 203.09 m			

firm limit at about 70 m depth.

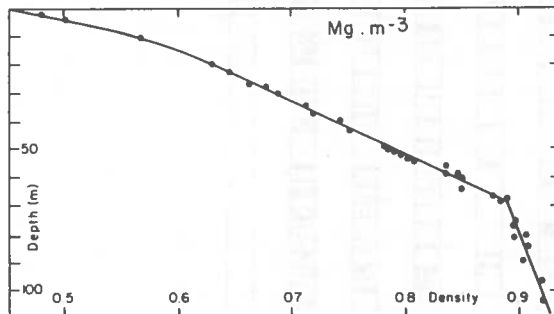


Figure 6. Density as a function of depth at the James Ross Island Site.

The first broken core appeared at 64.2 m depth and was heavily fractured on the top 30 cm. Down to 79.8 m only 4 % by length of the cores were broken. From 64.2 m until 150.5 m, the total length of broken cores reaches 13.7 m (16 % of the total core length).

Figure 7 shows the detailed logging of the different fractures observed in the core and Table 2 summarizes the main results.

Table 2

Depth (m)	Length of core broken (%)	Average core segment length (cm)
0 - 64	0	65
64 - 80	4	25
80 - 87	23	14
87 - 94	0.4	22
94 -107	11	19
107-116	16	15
116-130	4	14
130-144	12	9
144-145.7	56	-

Note: At 116.04 m the rate of penetration deteriorated and the cutters were modified to increase the hole diameter.

The depth given here (145.65 m) corresponds to the total length of core, but the depth actually drilled was 150.5 m. Thus, 4.85 m of missing core must be added to the logged core.

From 78.25 m (beyond which there is

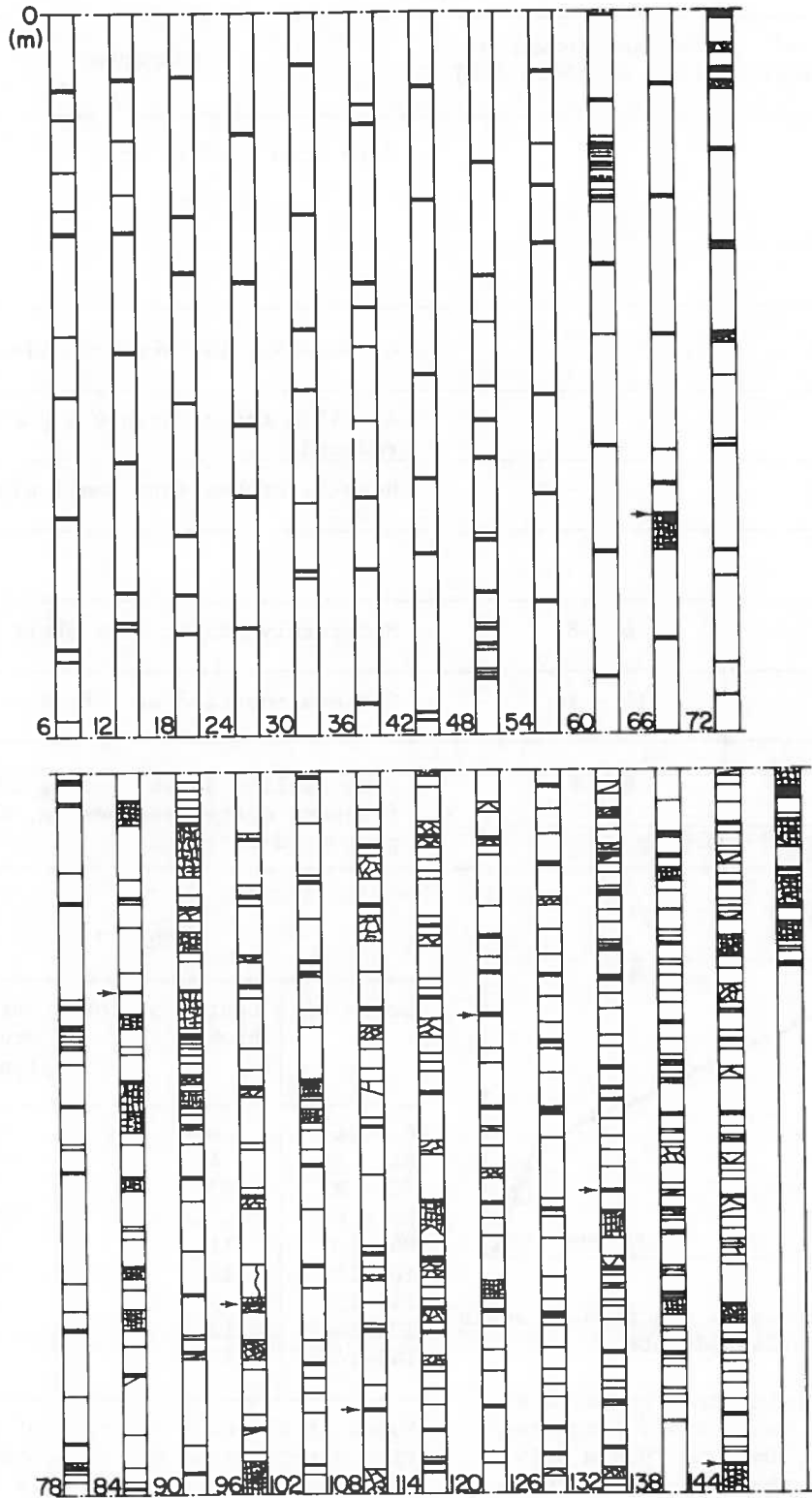


Figure 7. Core logging information for the James Ross Island site, showing the different core fractures observed in the ice. The thick horizontal lines correspond to the limit of the cores obtained in each run.

a difference between the depth reached by the drill and the depth corresponding to the length of cores retrieved) until 150.5 m, this deficiency represents about 6.7 %. This figure should therefore be added to the values given in Table 2. From 64 m until 150.5 m the total length of broken core is 13.4 m which represents 16% of the total.

DISCUSSION OF THE POSSIBLE CAUSES FOR THE DECREASE IN CORE QUALITY BEYOND THE FIRN-ICE TRANSITION

In view of the observations made, we believe that four parameters may have an effect upon the core quality. These are: (1) Cutter geometry and sharpness; (2) The physical properties of the ice; (3) Chip transport; (4) Stability of the drill (with respect to vibrations).

(1) Cutter Geometry and Sharpness

In all drillings, we would notice that an increase in core quality occurred after some slight modification was made to the cutters. At Dome C (II) this was at 137.00 m to 160.00 m, at site D 57 at 143.11 m to 151.76 m and between 178.54 m and 193.05 m, and at James Ross Island between 116.04 m and 129.05 m. Nevertheless we cannot state exactly what modification is the most effective. A round cutter is probably better than a cutter having the shape of the original SIPRE corer cutter blade. The barrel used at D 57 gave better cores than the first barrel used at Dome C, but this could also be the result of a better stability provided by three cutters.

It has also been noted that a frequent sharpening of the cutters is necessary. It is, further, difficult to know whether the back-rake and clearance angles used are completely satisfactory. More significantly, the problem is to know whether these angles are suitable for all types of ice encountered at different depths.

(2) The Physical Properties of the Ice

Let us consider the increase in the quality of cores gained after modifications made to the cutters. This improvement lasted from a few meters to more than 20 m. The way in which it sometimes ended leads us to the idea that it was produced by a sudden change in the physical properties of the ice. Site D 57 provides a good example of this observation. At 151.76 m the increase in

the quality of the cores was suddenly reversed after a few meters advance, and, until 154.84 m, we obtained 53 % broken cores, mainly at short discs, as if the ice was horizontally foliated. The same remark could also apply at 193.05 m.

In the James Ross Island Site drilling the phenomenon is not so clear, but it is of the same type. From 143.8 m down, 56 % of the cores were suddenly broken. Such variations in the physical properties of the ice are not surprising. In the thermal drilling made in Adelie Land at D 10 in 1974, the cores had many horizontal fractures between 150 m and 170 m and again from 261 m to 264 m. Deeper (to the final depth of 304 m) despite a strong stratification, core quality was excellent.

Intuitively, we think that the ice temperature has an influence. Cold ice is more brittle and can be more easily broken even if its mechanical strength is higher. If we compare the cores obtained at D 57 and James Ross Island, where the mean ice temperatures are -32°C and -14°C respectively, we do not see any significant difference in core quality. The percentage of broken cores is of the same order (13 % and 16 % respectively). At Dome C, we did not make a precise measurement of the length of broken cores. Nevertheless, the percentage of broken core was certainly higher than at either of the two other sites. However, the core barrel was not identical in all cases, and therefore it is hardly valid to make a direct comparison.

(3) Chip transport

The following observation was made mainly at Dome C. Below the firn-ice transition, the size of chips decreases and a large percentage of the chips is in the form of ice powder. This powder has a very high coefficient of friction, causing difficulty in moving the chips up the auger flights. This results in reduced run lengths. This seems more pronounced in colder ice.

Table 3 shows the average run length as a function of depth, at four sites.

When the drill surfaces, we observe that the lower part of the auger flight is full of compacted powder whereas the barrel is incompletely full. From this observation it may be inferred that the chips occurring between the core and the wall of the core barrel tube are compressed, causing torque to be transmit-

Table 3

Depth (m)	Dome C (I)	Dome C (II)	Site D 57	James Ross Is.
0-20			1.17	0.92
20-40			1.13	0.92
40-60	1.00	0.98	1.04	0.80
60-80	0.87	0.93	0.96	0.93
80-100	0.80	0.83	0.90	0.82
100-120	0.72	0.68	0.76	0.71
120-140	0.62	0.59	0.75	0.73
140-160		0.61	0.48	0.65
160-170		0.55	0.53	
170-180		0.48	0.60	
180-190			0.47	
190-203			0.50	

Note: Run lengths shown are in meters

ed to the core. This torque may cause the core to fracture into the small discs.

(4) Stability of the Drill

It is unusual to recover completely broken core. Generally, one or two pieces of the core are fractured. This irregularity suggests that a type of instability appears during the rotation of the drill. A similar phenomenon is observed in drilling in metals resulting in non-circular hole shapes. The vibrations set up in the drill unit as a result of this could induce stress fractures in the ice. We obtained much better results with the more stable three cutter barrel. Even then, vibrations do not seem to be completely suppressed, and it would be worthwhile examining the following improvements: (a) exact centering of the inner barrel axis with the outer barrel axis; (b) centering of the outer tube and the upper part of the drill unit in the hole.

CONCLUSION

The electro-mechanical drill shows many advantages, e.g. light weight and efficiency. We drilled to 140 m and 180 m in 70 h and 100 h respectively at Dome C and to 203 m in 130 h at Site D 57. The drill can be operated by two people in a safe and reliable manner. But, when working in ice, the quality of the cores must be improved, and if deeper cores are required, it will be necessary to increase the length of each run by solving the problem of powder generation and poor chip transport.

ACKNOWLEDGMENTS

We thank John Rand and Henry Rufli for their valuable help in designing the drill. Thanks are also due to the U.S. National Science Foundation, the Instituto Antártico Argentino, the Terres Australes et Antarctiques Françaises and the Expéditions Polaires Françaises for supporting the four drilling operations.

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DEEP CORE DRILLING: ELECTRO-MECHANICAL
OR THERMAL DRILL?

D. Donnou, F. Gillet, Laboratoire de Glaciologie
A. Manouvrier, J. Perrin, et Géophysique de l'Environnement,
C. Rado and G. Ricou C.N.R.S., Grenoble, France

ABSTRACT

In 1977/78 at Dome C, Antarctica, it was not possible to drill deeper than 905 m because of hole closure. The thermal drill has subsequently been modified to drill deeper in a fluid filled hole. Simultaneously, we have developed an electro-mechanical drill which employs a centrifuge device for separating chips and drilling fluid. Both sets of equipment are described here, as well as the main results obtained in the first tests made in Adélie Land in 1981/82.

INTRODUCTION

The thermal drill used in 1977/78 at Dome C, to core to a depth of 905 m, has been modified in order to drill in a fluid filled hole. The main advantage of this thermal equipment is to give runs of up to 6-8 m without difficulty, but its penetration rate (6-7 m/h) is relatively low. Due to the high electrical power needed at the head (5-6 KW) and auxiliary requirements, the number of cable conductors is high, resulting in a rather large cable diameter.

An electro-mechanical drill which requires about 1 KW to rotate the cutters and which has a penetration rate of 20-40 m/h appears to be a good alternative. However, for deep drilling, it is necessary to have runs as long as possible. In a mechanical drill, this introduces a problem associated with the transport of cuttings. To increase the efficiency of chip transport, we developed a system using a centrifuge.

A first test was made this year in Adélie Land for both drilling systems.

THERMAL DRILL

The unit (Fig. 1), which was used in Adélie Land (to 304 m) and on a temperate glacier (Gillet, *et. al.*, 1976), has also been used at Dome C (to 905 m), in the Glacier d'Argentieres (to 245 m) and again in Adélie Land (to 348 m). For this last drilling operation in 1981/82, some modifications were made to the drill:

- (1) The electrical insulation of the bare wire was installed with two types of support. These are, a stainless steel crown covered with a thin deposit of chromium oxide and a machined ceramic fixed in a hollow stainless steel crown.
- (2) The thermal insulation required in the suction tubes in the core barrel and on the melt tank is produced by applying a layer of epoxy resin on the inside wall of the tubes by a centrifuge process.
- (3) The OD of the drill was increased to 140 mm to be compatible with the hole produced by the electro-mechanical drill.

To work in a fluid, the vacuum pump was replaced by a small, 30 W, 220 V vibration pump. The flow may be varied from 5 to 300 l/h but is generally adjusted at 40 l/h. It is located at the top of the melt tank, so that no water flows through it.

Heating of the suction tubes and of the melt tank was increased and can be varied separately from 0 to 350 W for the tubes and from 0 to 500 W for the tank (Fig. 1).

The maximum power is used at the beginning of each run until the permanent water circulation is established. Three different temperature measurements

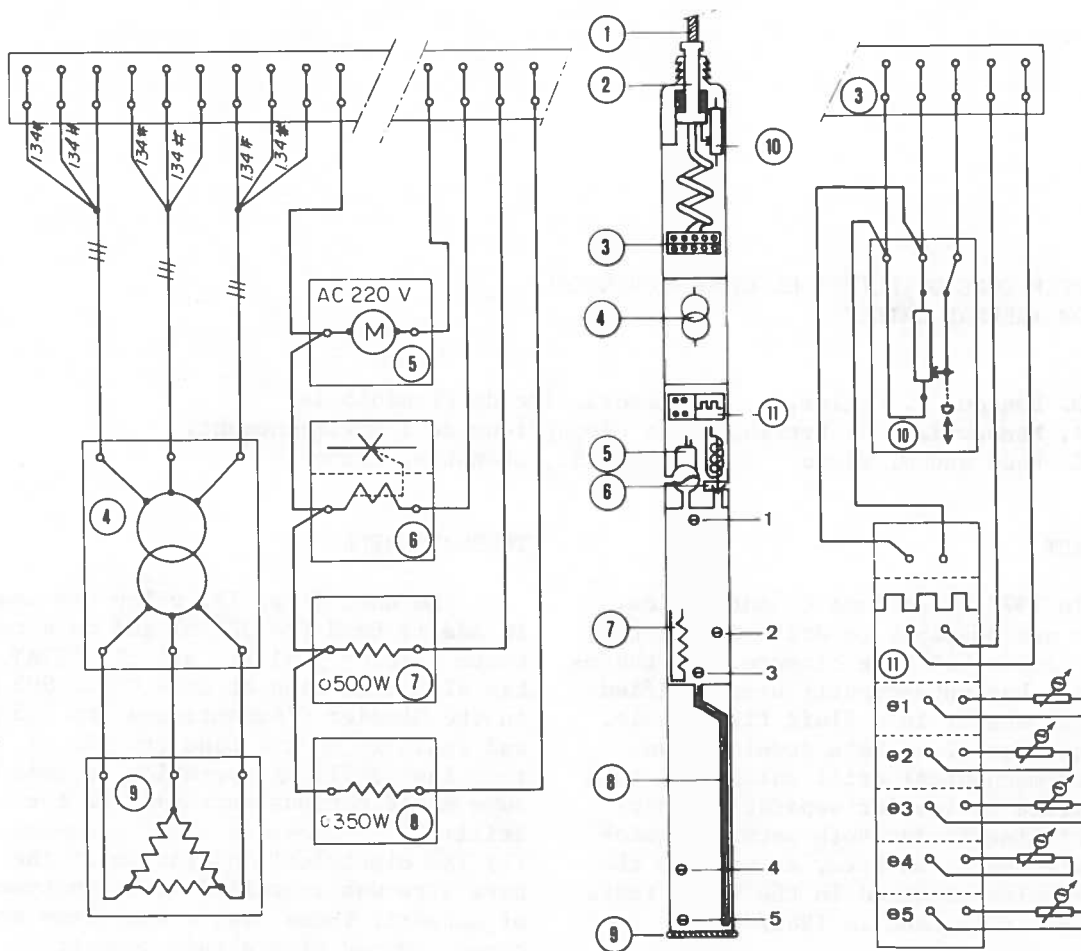


Figure 1. Schematic diagram of the thermal drill unit (electrical diagram). (1) Electro-mechanical cable. (2) Cable termination. (3) Junction box. (4) Transformer. (5) Pump. (6) Valve. (7) Heating element (melt tank). (8) Heating element (tubes). (9) Bare resistance wire. (10) Suspension. (11) Electronic switch (for θ measurements). (θ_1) Top of melt tank (water level measurement). (θ_2) Melt tank. (θ_3) Top of the suction tubes. (θ_4) Drilling fluid. (θ_5) Head.

were made at the head, top of the suction tubes and the melt tank. The signals are transmitted consecutively, to the surface through two conductors, using an electronic switch. It should also be worthwhile to measure the temperature of the drilling fluid near the head, as this measurement would be an indirect indication of the water level in the hole.

The cable was the same 1000 m electro-mechanical cable already used at Dome C (16 mm ϕ ; 6 conductors at 1.34 mm² 13 conductors at 0.93 mm²). For deep drilling, we are planning to use a cable with 8 conductors at 1.34 mm² with a bifilar line in the core. The cable dia-

meter is 16 mm and the weight 930 Kg/Km. For heating of the head, 2 x 3 conductors would be used at 1000 V. Two conductors would be used for auxiliaries and the bifilar line for telemetering.

RESULTS

In 1981/82, we drilled a dry hole to 329 m. Kerosene was then put in the hole before drilling continued to 348 m depth.

With a 2.8 m length core barrel and runs between 2 and 2.5 m, we had no problems circulating the water. It seems possible to increase the barrel length to 6-8 m without any major difficulties.

The penetration rate (Fig. 2) is the same as in a dry hole and varies from 5 to 7 m/h, corresponding to power on the head from 3.5 to 5 KW.

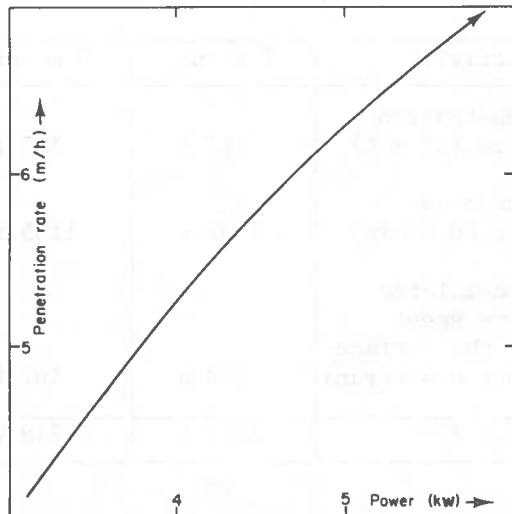


Figure 2. Penetration rate as a function of power on the head.

Core quality is excellent. We obtained completely transparent cores without any fractures, whereas, a few meters before, we had foliated cores as previously obtained in the 905 m dry hole at Dome C.

The amount of melt water recovered during each run, is between 14 and 18 l. The diameter of the cores is the same as in a dry hole and is about 115-116 mm.

ELECTRO-MECHANICAL DRILL

This unit (Fig. 3) is 140 mm in outside diameter and 8 m long. The termination and anti-torque sections of the shallow electro-mechanical drill is utilized. A 380 V, 3 phase, 3.7 KW, 2800 RPM submersible electric motor rotates the centrifuge basket which is made from a 110 mm diameter, 3 m long aluminium tube. One hundred holes are drilled in it and it contains a stainless steel, 0.5 mm thick filter. At the lower end, a propeller with three adjustable blades, is used as a circulation pump and gives a satisfactory vertical flow to the chip loaded fluid. The tube is connected to a 3 stage gear reducer (1:27) giving a rotation speed of 105 RPM to the core barrel. The chip loaded fluid flows to the inner side of the centrifuge basket through a 40 mm diameter hollow shaft in

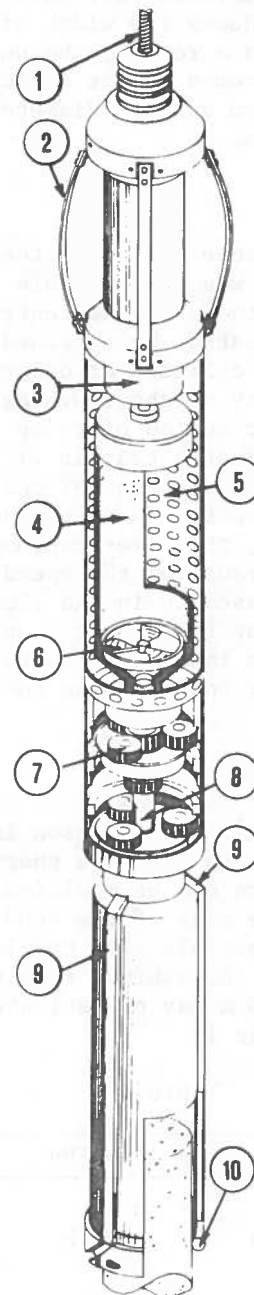


Figure 3. Schematic diagram of the electro-mechanical drill. (1) Electro-mechanical cable. (2) Springs. (3) Submersible motor. (4) Filter. (5) Centrifuge basket. (6) Propeller. (7) Gear reducer. (8) Hollow shaft. (9) Rectangular tubes. (10) Cutters.

the gear reducer. The head has three round cutters. The chips produced, are

transported by the fluid through three rectangular tubes soldered onto the 118 mm (ID) x 121 mm (OD) stainless steel tube of the core barrel. This rectangular shape reduces the width of the cutters, and, as a result, the quantity of chips to be removed. The diameter of the core is 115 mm and the diameter of the hole is 143 mm.

RESULTS

Due to some defect in the core catchers, it was not possible to retrieve cores. Nevertheless, the centrifuge device was tested. We obtained a 3 cm thick hollow cylinder of compressed chips with a density of about 0.6 Mg m^{-3} . The regular distribution of these chips along the tube indicates that it will be possible to store an amount of chips allowing runs of up to 3 m to be made.

However, the power consumption was very high because of the speed of the centrifuge assembly in the fluid. This speed, causing frictional drag, has to be reduced. Some laboratory tests need to be made in order to determine the optimum value.

CONCLUSIONS

After this field season in Adélie Land, it appears that the thermal drill described here can be modified for deep drilling. The size of the 4000 m long cable is compatible with the logistics constraints. The minimum time needed to drill to 3500 m may be estimated as shown in Table 1.

Table 1

Activity	6 m run	8 m run
Penetration rate (6 m/h)	583 h	583 h
Winching (at 60 m/min)	568 h	425 h
Accumulated time spent at the surface (est 0.5 h/run)	291 h	218 h
Totals	1442 h	1226 h

These figures (50-60 days) show that it is possible in principle to drill to 3500 m in a single summer season.

The electro-mechanical drill used this year is an interesting device, but

more tests are needed before its deployment in a deep drilling operation.

Table 2 shows that the time needed to drill to 3500 m is very dependent on the length of each run.

Table 2

Activity	2 m run	3 m run
Penetration rate (30 m/h)	117 h	117 h
Winching (at 60 m/min)	1702 h	1135 h
Accumulated time spent at the surface (est 0.4 h/run)	700 h	467 h
Totals	2519 h	1719 h

Table 2 indicates that 72 -105 days would be needed to drill to 3500 m with the electro-mechanical drill.

These results encourage us to build a thermal drill with a 4000 m cable and associated winch. If the final tests of the electro-mechanical drill are satisfactory, and, especially if the run length can be increased to over 3 m, we will then use it interchangeably with the winch and cable system of the thermal drill.

ACKNOWLEDGMENTS

Thanks are due to those who helped operate the drills in Antarctica. We would like to thank the Terres Australes et Antarctiques Françaises and the Expeditions Polaires Françaises for financial and logistical support.

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ICE DRILLING AT
CAPE FOLGER, ANTARCTICA

V.I. Morgan, Antarctic Division,
A.P. McCray and Department of Science and Technology,
E. Wehrle Kingston, Tasmania, Australia

ABSTRACT

The use of a modified USA CRREL thermal drill is described and discussed.

INTRODUCTION

Ice drilling undertaken at Cape Folger, Antarctica, in 1981/82, is a continuation of an extensive glaciological investigation of the Law Dome ice cap, which has been studied since 1957 (Budd, 1970). The boreholes drilled in 1969 were used to study ice deformation and the core was used to study ice crystal size, crystal orientation fabrics, oxygen isotopes and ice flow properties with depth (Budd and Morgan, 1977). The latest drilling is specifically designed to clarify certain peculiarities in the ice flow which were observed previously (Russell-Head, 1979). There appear to be large irregularities in the magnitude and direction of shear strains.

The two boreholes lie along a surface flow line, one over a bedrock high point, the other over a dip in the bedrock, 300 m down glacier. Both holes extend to within a few meters of the bed, as deduced from the presence of small rock fragments contained in the lowest core retrieved from each hole.

THE DRILL UNIT

A modified USA CRREL thermal drill (Ueda and Garfield, 1969; Bird and Ballantyne, 1971) was used. The core barrel has been lengthened and the melt tank enlarged to allow a 2 m long core

to be taken. The heater head assembly is that constructed by Russell-Head (1979) and uses a single element cast in a copper annulus. This has proven to be much more reliable than the previous system of cartridge heaters pressed into an aluminum head. The copper head is slightly larger than the drill barrel, to facilitate the passage of the drill in a hole which is closing.

The temperature at the head and the melt tank vacuum are both monitored. The head temperature is not critical with the copper head, since it does not melt down as easily as the aluminum one did, but it is a useful indicator of thermal contact between the head and the ice, particularly when reaming.

The melt tank vacuum reading shows up malfunctions in the water extraction system, failures of which can result in freezing in of the drill.

An hydraulic motor is used to raise and lower the drill and an hydraulic ram, which lowers the cable sheave, is used to feed the drill when coring. Better quality cores and a somewhat faster drilling rate are obtained when using this feed system.

THE DRILLING OPERATION

Due to the lack of hydrostatic balance in the hole during drilling, and the relatively high temperatures near the bottom of the hole, large closure rates of up to 1.3 mm/h were encountered. This introduced considerable difficulty during drilling, and

towards the base of the holes, several reaming runs (in which the drill is operated at slow feed rate, with both heater and vacuum pump on) were necessary before taking each core. Drilling was stopped in the first hole at 301 m due to low penetration rates and the danger of losing the drill due to rapid hole closure. The radar equipment indicated an ice thickness of 303 m at this site.

In the second hole, after taking a core containing rock fragments, no progress was being made, possibly due to the existence of larger particles, so drilling was stopped at 344.5 m. The radar equipment indicated an ice thickness of 350 m at this site. However, the radar reflection will probably be from the highest layer of substantial rock fragments, so the exact bedrock depth may not have been established.

INSTRUMENTATION

The holes were logged for temperature, diameter and inclination. A platinum resistance thermometer connected to a Leeds and Northrup 8078 resistance bridge gave temperatures to $\pm 0.01^\circ\text{C}$. Schaevitz LSRP-5 and LSRP-30 sensors are used to measure the borehole inclination. For short period monitoring (of order 50 h) apparent tilts were erratic, possibly due to settling of the instrument in the hole. The latest boreholes have been relogged (1982/83) after periods of 0.5 a and 1 a and inclination changes of up to 12° have been measured in the lower levels (McCray, unpublished).

DISCUSSION

Eight boreholes have now been drilled approximately along a flow-line running from the dome summit to Cape Folger on the Law Dome. The holes near the edge, extend well into Pleistocene ice and the latest two penetrate practically to bedrock. Research is presently concentrated on climatic change as interpreted from the oxygen isotope data. Ice dynamics studies are in support of this research.

For the future, an improved thermal (or mechanical) drill, capable of drilling in a fluid filled hole, would allow a borehole to be drilled from the dome summit to bedrock where the ice thickness is about 1300 m. This is a particularly favorable site, as absolute dating may be obtained from the seasonal signal in the $\delta^{18}\text{O}$ variations that are locked in because of the high accumulation rate

(approximately 1 m/a).

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A SIMPLE HOT-WATER DRILL FOR PENETRATING ICE SHELVES

R. Verrall, DREP Esquimalt, Canada
D. Baade, DREP Esquimalt, Canada

A simple hot-water ice drill capable of making holes 20 cm in diameter through ice at least 50 metres thick was designed at the Defence Research Establishment Pacific and tested on the Ellesmere Island ice shelves. The drill is built primarily with commercially-available equipment, the amount of in-house construction being kept to a minimum. Using readily available fuel, Arctic diesel or turbo fuel, a hole through the 50-metre-thick shelf was drilled at a rate of 11 m per hour. The paper discusses the drill construction and tests, and indicates a number of weak points in the design.

I. INTRODUCTION

A simple hot-water ice drill capable of penetrating the 50-metre-thick ice of the Ice Shelves on Ellesmere Island, has been designed, built and tested by the Arctic Acoustics Group at DREP. Because of the size of the equipment we wished to lower below the ice, it was necessary to develop a technique for drilling holes at least 20 cm in diameter. It was decided that a hot-water drill, although it would not penetrate as fast as a mechanical drill, would be lighter, less expensive and less complicated to operate in the field.

II. THE DRILL

Basically, the drill consists of a water heater, a water pump, a hose to feed the water down the hole and a hose to recover it. In order to reduce the suction head, the hole is kept full of water as long as possible. The ice is quite impermeable, and the head of water is maintained until the drill runs into cracks or porous ice near the bottom of the ice. At that point, the water level in the hole drops to the ambient level of the ocean, the free-board being some 10% of the ice thickness. The diagram in Figure 1 shows a schematic layout of the drill. It indicates that the water may be routed either to the ice hole or to a snow melter, and it may be picked up from either of the two. This flexibility is required because the water to start the procedure is made by melting snow and because it is necessary to top up the water in the hole from time to time.

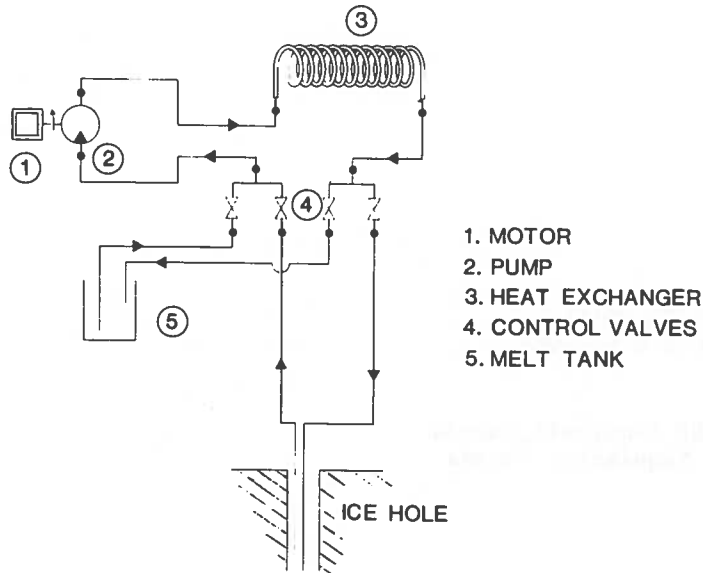


Figure 1. Schematic diagram of the hot-water drill. The pump draws the water from either the ice hole or the snow melter (#5). After the water is heated it can be directed, by means of valve setting, back to either location. The snow melter, which can be heated separately, is used to generate enough water to begin the drilling operation. It is then taken out of the circuit, and the hole drilling begins.

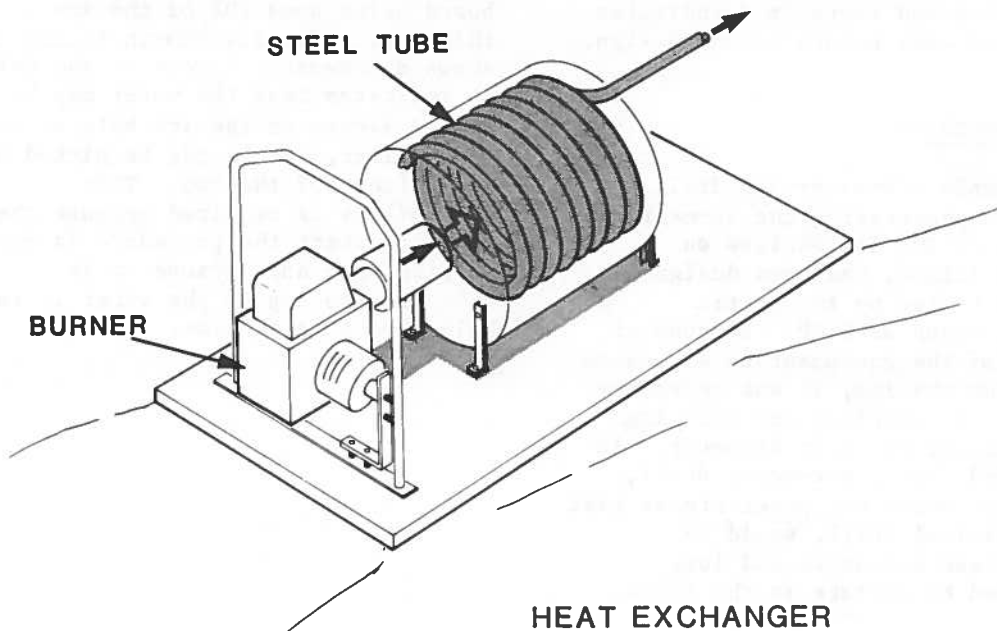


Figure 2. An illustration of the water heater. Either diesel fuel or turbo fuel (JP-4) can be used to supply the heat. The total weight of the unit is about 150 kg.

a. Water Heater

The water heater is a commercial APEX steam generator purchased from Northwest Malsberry, Seattle. It consists of a coil of steel tubing (1/2 in. sched 80), which acts as the heat exchanger, and a burner unit that is similar to those found in a house furnace (Figure 2). It puts 235,000 BTU/Hr (68.9 kW) of heat into the water when a fuel nozzle rated at 3.5 US gal/Hr is used. The actual fuel consumed was 3.2 US gal/Hr (12.1 l/Hr) of turbo fuel (JP-4) which has a heat content of approximately $3.2 \times 135,000 = 432,000$ BTU/Hr (126.6 kW). This implies the heat exchanger has an efficiency of .54.

A propane-fired water heater was also tested at the laboratory and in the Arctic. It was the 'Nordic' model, made by Edvan Agencies in Vancouver, B.C. Its heat-exchanger coil was copper tubing, and the unit was much smaller and lighter than the steam generator (35 kg vs 170 kg). In spite of this very real advantage, it was not used for drilling holes on the ice shelves. It would produce only 97,000 BTU/Hr (28.4 kW), which is less than half of that produced by the oil-fired unit. Also, propane is a fairly exotic fuel in the Arctic, whereas diesel fuel

and JP-4 are very common. Propane fuel tends to be cumbersome because the empty tanks are so heavy. Another objection is that the propane tank must be heated in the cold weather to assure a sufficient flow of gas. (This was done with waste heat from the heater.) However, the unit did work well, and, if a future application demands a lightweight water heater instead of high heat output, and if the heavy propane tanks are not a problem, the propane heater would be the one to choose.

b. Snow Melter

A supply of water is required to fill the hoses and heat exchanger so that the drilling process can begin. The snow melter shown in Figure 3 is simple, light and reasonably efficient. It consists of two concentric barrels. The snow is melted in the central drum, and the flames from the burner rise up the gap between the drums. The water is removed through a plumbing fitting and valve at the bottom. The fuel burner, which was designed for easy attachment, is the same unit as is used on the main heat exchanger.

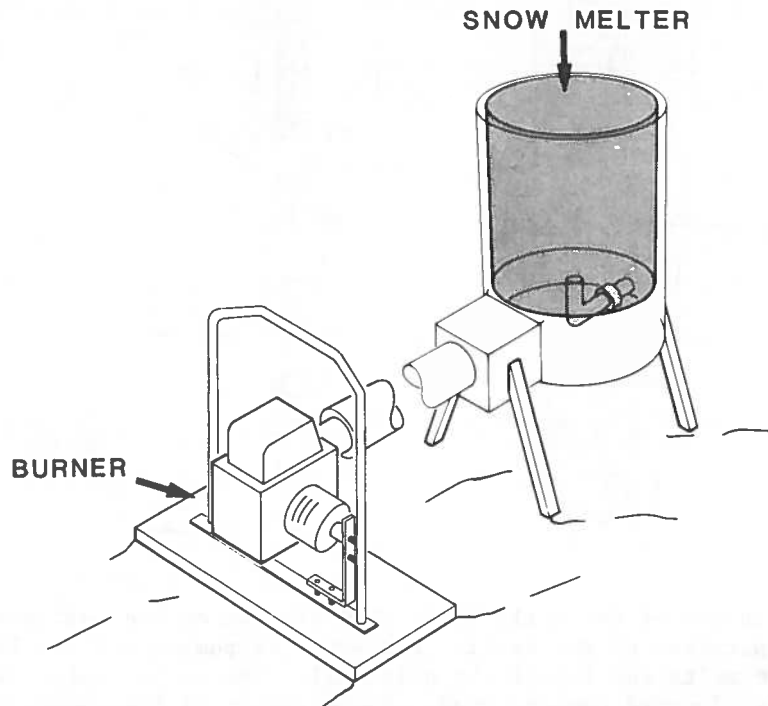


Figure 3. A snow melter for creating the initial water to start the hot-water drill. The snow is melted in the inner tank of two concentric tanks. The outer tank is present to guide the hot air around the melting tank. The burner was the same unit as was used with the water heater.

c. Drilling Head

The drilling head is shown in Figure 4. It consists of a 1.5 metre length of 1 inch plumbing pipe with a 20 kg weight attached to it. Screwed to the top of the pipe is an attachment that picks up the return water and feeds it to the 'return' hose. Also, it prevents the pipe from descending until the ice supporting it has melted; it thus ensures a minimum diameter for the hole.

The simple length of pipe seems to work as well as other more elaborate drilling heads that were designed and tested. A high-speed jet of water is capable of sinking a smaller hole at a greater speed. But, because a fairly large hole was desired, the jet nozzle and associated high-pressure pump were not required. It was found that a

shorter length of pipe was not as successful as the 1.5 m length. With a short pipe, the hot water did not have sufficient time to lose its heat to the ice, and the pick-up water was still hot. This caused the temperature of the outlet water to rise to an uncomfortable 90°C, and an excess of heat was lost from the hoses and fittings on the surface. Lengthening the pipe cured this.

When the pipe penetrates the bottom of the ice, the hot water is diluted by cold sea water and is swept away, and the melting action is lost. When this happens, the operator reverses the connections at the surface so that the return hose becomes the feed hose and vice-versa (see Figure 4). The hot water is now blown out the holes in the attachment at the top of the pipe and descends through the ice

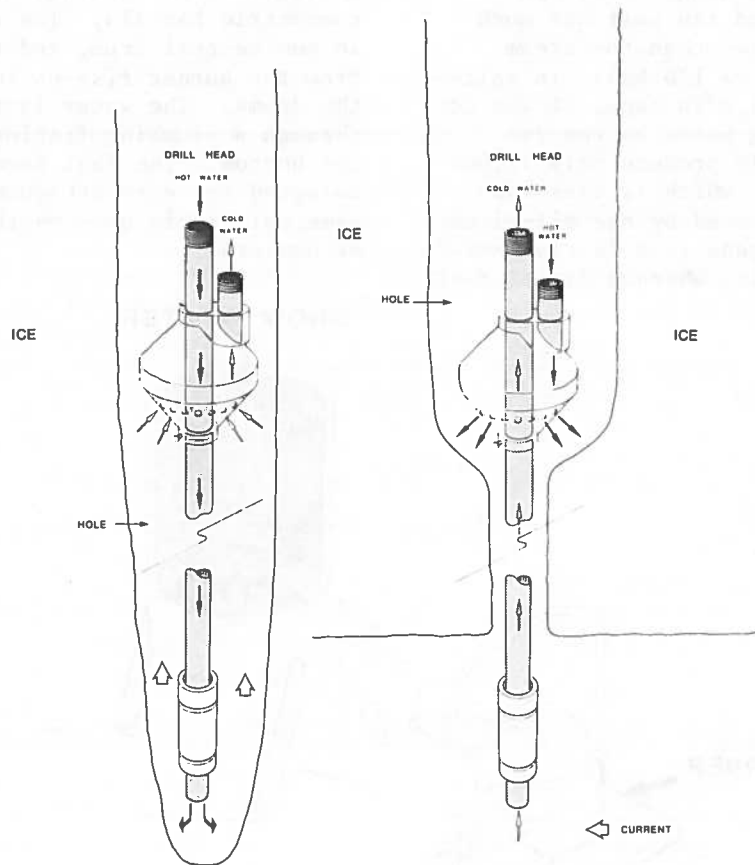


Figure 4. Illustrations of the drill head. The diagram on the left shows the usual operation of the drill. Hot water is pumped out the bottom of the pipe and melts the ice of the hole wall. The cooled water is picked up by the perforated conical head. The diameter of this head sets a minimum size for the hole. The pipe is about 1.5 metres long. The diagram on the right indicates the reversal in water flow once the pipe has dropped below the bottom of the ice. Hot water is ejected from the conical head, and cold water is picked up by the pipe.

to the water below, melting as it goes. Because the sea water picked up by the pipe is colder than the usual return water, the drilling speed drops; however, this is acceptable since only about 1.5 m of ice must be drilled in this way. Once the 'sizing' attachment falls into the water, the hole is complete.

d. Brake Drum

In order to keep the hole plumb, a weight is attached to the drill head and a lifting force is exerted on the hoses at the surface. This produces a pendulum effect. If the drilling head drifts off to the side, there will be a restoring force to bring it back to the plumb. The lifting force is produced by a brake drum, shown in Figure 5. Both hoses are wrapped around the drum at least one and a quarter turns so that there will be no slippage. The braking action is produced by a length of rope wrapped around the drum and attached to the frame. A spring scale in the high-tension side of the rope indicates the braking force exerted on

the drum. Since there is virtually no tension in the other end of the rope, the retarding force on the hoses is simply the reading on the spring scale. The braking force is quite constant because the spring in the scale stabilizes the operation. For example, if the rope grabs a little and increases the tension, the spring lengthens, and this extra length causes the rope to slacken off and reduce the tension to its normal value. Usually a force of 7 to 9 kgf is used, and a mass of 20 kg is attached to the drill head. To make it easier to put the hoses on the drum and to take them off, the drum was built to pivot upwards about one end of the shaft. The other end of the shaft is then in the air, and a loop of hose can easily be thrown about the drum. The free end of the shaft is then dropped back onto a yoke support.

The drum is also used as a capstan to bring up the pipe and hoses. The brake rope is removed and an electric drive is attached to the hub of the drum. The hoses are then pulled out onto the ice with the capstan providing most of the lifting power.

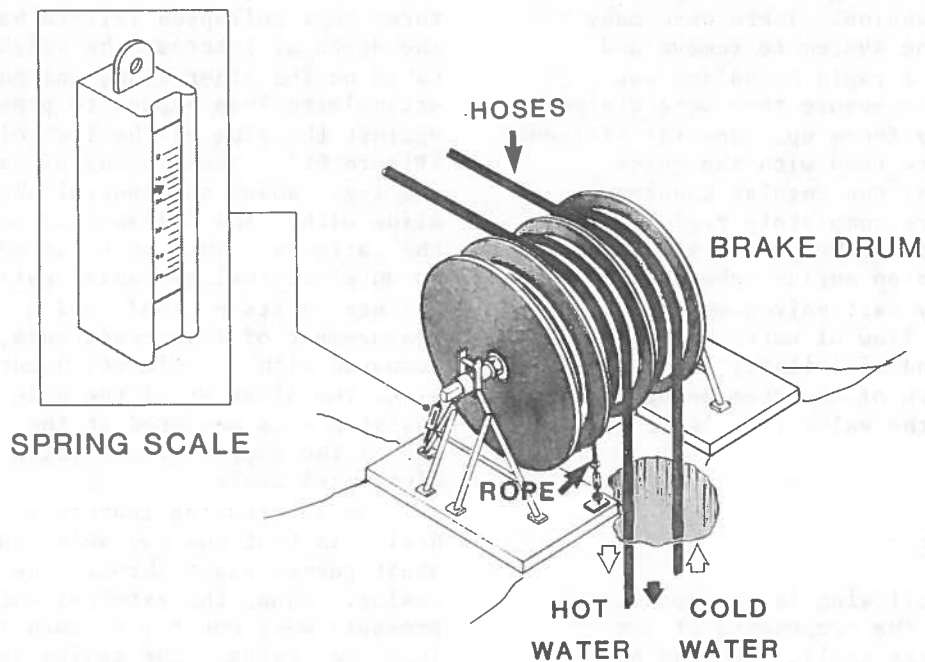


Figure 5. An illustration of the brake drum that is used to provide an upward force on the hoses. This tension, which is less than the weight of the drill head, helps to keep the hoses (and thus the hole) plumb. The inset indicates the spring scale which shows the retarding force. An electric drive can be fit over the square shaft. This turns the brake into a capstan to help raise the drill.

e. Pumps, Plumbing and Motor Generators

A Mann West gear pump (CJN, 1 inch) was used to pump the water out of the hole, through the heat exchanger and down the hole again. It was powered by a 5/8 HP (470 W) electric motor, and the electric power was supplied by a 5 kW Briggs and Stratton motor-generator. The generator also provided power to run the fuel pump on the heater.

The hoses were Gates EPDM (ethylene propylene diene tertolymer) (2.54 cm I.D., 3.61 cm O.D.). They maintained adequate flexibility in the cold weather although they were easier to handle when they were filled with warm water. On the surface, the hoses were coiled in insulated boxes, one box for the feed line and another for the return hose. Before the insulated boxes were used, the hoses rapidly melted their way into the snow. This wasted a substantial amount of heat and made the hoses hard to handle.

All attachments to the hoses were made with 'quick disconnects' (Hansen 'Straight-Through One Inch Brass Couplers'). They greatly facilitated disconnecting and draining hoses whenever anything went wrong or after a drilling session. There were many hoses in the system to remove and drain, and a rapid technique was necessary to ensure they were drained before they froze up. Special silicone O-rings were used with the quick disconnects; the regular neoprene O-rings were completely rigid in the cold and had to be pre-warmed in hot water or in an engine exhaust.

Whitey ball valves were used to direct the flow of water. They worked reliably and efficiently, only a quarter turn of the stem being required to change the valve from 'full off' to 'full on'.

f. Cost

The following is an approximate costing of the components of the oil-fired ice drill. It does not include the shop costs of assembling the parts or of making the snow melter or brake drum. Also, it does not include any spares.

Heater unit	(Can) \$3000.
Oil burner	330.
Drill hose (\$1.20/foot)	700.
Couplings (10 x \$30.)	300.
Valves (5 x \$108.)	540.
Electric Motor	180.
Gear pump	60.
Motor generator	370.
Misc. (Hose fittings, spring scale, etc.)	100.
Total	\$5580.

g. Hole Calipers

It is very useful to be able to measure the diameter of the completed hole. After the passage of the drill head, heat is continually taken from the water by the surrounding cold ice but slowly added to the water from the warm hoses. Consequently, it is difficult to predict whether the hole will grow or shrink after the head has gone by. This information has a bearing on subsequent modifications of the drill. In order to measure the hole's diameter remotely from the surface, a set of hole calipers was designed and built. It is shown diagrammatically in Figure 6. With its weight carried by one of the two support ropes, it is lowered with its three legs collapsed (Figure 6a). At the depth of interest the weight is taken on the other line, and the three articulated legs expand to press against the side of the ice hole (Figure 6b). The process of expanding the legs causes the central shaft to slide within the cylindrical body of the calipers. This shaft is connected to an electrical variable resistor (linear in its motion), and a measurement of this resistance, when compared with a calibration curve, gives the diameter of the hole. The resistance is measured at the surface, one of the support lines being an electrical cable.

An interesting feature of the device is that the moveable centre shaft passes right through the main casing. Thus, the external water pressure does not try to push the shaft into the casing. The casing is made of a flexible-walled tygon tubing and is filled with silicone fluid in order to equalize the pressure inside and outside. Since there is minimal pressure difference, the light fitting O-rings act as rod wipers rather than

as pressure seals and permit free rod movement at any depth.

III. RESULTS

For the test on the ice shelf in April 1982, turbo fuel was used with the nozzle rated at 3.5 US gal/Hr (13.2 l/Hr), and the hole was sunk at the rate of 11 metres per hour. With a 'sizing' attachment of 17 cm in diameter, a hole was drilled that, in the upper 8 metres, was 23 cms in diameter with a variation of 1 cm.

(Problems with the equipment prevented the rest of the hole from being logged. Presumably, the hole decreased in diameter at the bottom.) As far down as could be seen, the hole was very round and the walls were smooth.

During tests at other locations in the Arctic in 1981, it was found that hot-water drills can easily do certain types of jobs that would be very difficult for mechanical drills. For example, a hole was drilled through the ice freeing a cable that had been frozen in place. This allowed a suspended instrument to be recovered.

HOLE CALIPERS

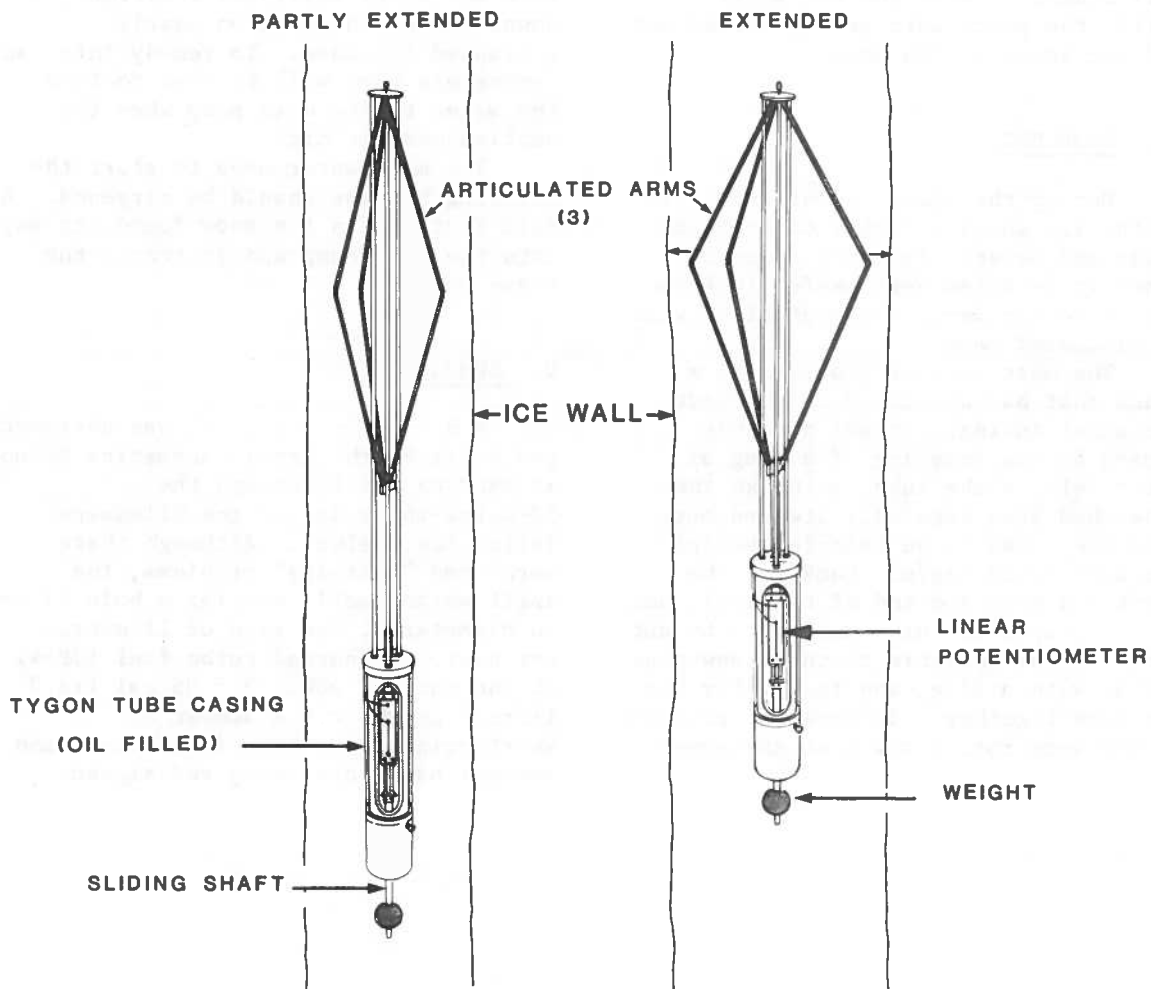


Figure 6. The hole calipers, a device for remotely measuring the diameter of the ice hole. The sliding shaft is connected to the bottom end of the articulated arms. When the weight is taken by a line attached to the framework, the weight pulls the shaft down, and the three arms lie together tightly. When the weight is taken by a line attached to the central shaft, the framework slides down, and the arms expand until the joints meet the walls of the hole. The amount of relative motion, and hence the diameter of the hole, can be inferred from the resistance of the linear potentiometer.

Following the cable through the ice added no extra difficulty to the procedure. Originally, several cable-following mechanisms had been designed, but they were not necessary. It is possible that the heat in the water was conducted ahead by the cable, thus warming the ice and directing the melting action. Another job that could not have been easily done by a mechanical drill was that of freeing wooden posts in the ice and lowering them to a greater depth. These posts, which suspended a small building on the ice, had effectively been lifted by a summer's melt; the water had run down cracks and fissures leaving the posts and building higher in the air by about half a metre. With the hot water drill, the posts were easily melted out and set lower in the ice.

IV. PROBLEMS

During the operation of the drill on the ice shelf a number of problems arose and several failures occurred. Since it is often very useful to know what does not work, these problems will be discussed here.

The most serious problem was a crack that had developed in the heat exchanger tubing. It was probably caused by the freezing of a slug of water left in the tube, although the tubes had been carefully steamed out. This break had to be repaired before the work could begin. Luckily, the break was near one end of the coil, and only a couple of turns needed to be cut off. It was possible to cut a new pipe thread with a file, and the system was put back together. To cure the problem in the long run, a new heat exchanger

is being designed. It will be easier to drain and will not be so sensitive to a small amount of left-over water.

A second problem was the overloading and subsequent burn-out of the 5/8 HP electric motor. The flow-rate of the water was quite high and the pressure drop across the heat exchanger rose to over 100 psi (690 kPa), presumably because of the build-up of sediment or scale. Too much power was required to drive the pump, and the motor burnt out. In future, the new heat exchanger will introduce a much smaller pressure drop. Alternatively, the flow rate could be decreased.

It was difficult to prime the pump when the water level was 5 metres down. Also, the suction nearly collapsed the hose. To remedy this, an immersible pump will be used to feed the water to the main pump when the suction head is high.

The melt water used to start the drilling process should be screened. A nail that was in the snow found its way into the gear pump and destroyed the brass gears.

V. SUMMARY

A hot-water ice drill was designed and built by the Arctic Acoustics Group at DREP to drill through the 50-metre-thick ice of the Ellesmere Island Ice Shelves. Although there were some "teething" problems, the drill worked well, melting a hole 23 cm in diameter at the rate of 11 metres per hour. It burned turbo fuel (JP-4) at the rate of about 3.5 US gal (13.3 litres) per hour. A number of shortcomings have been identified, and several parts are being redesigned.

"CLIMATOPIC" THERMAL PROBE

F. Gillet, C. Rado, Laboratoire de Glaciologie
G. Marec, M. Maitre, et de Geophysique de l'Environnement
J. Perrin and G. Ricou C.N.R.S., Grenoble, France

ABSTRACT

Stable isotope analysis of the melt water recovered by a thermal probe can give a continuous record of climatic changes. The "climatopic" probe has a small diameter (43 mm) and needs only low power (2250 W) on the head to reach practical drilling speeds usually lying between 5 and 8 m/h. With runs up to 6 m we hope to drill deeper than 3000 m in a single summer. Because of the limited power requirements, the necessary cable weighs only 1050 Kg and the overall equipment is relatively light (8000 Kg completely packed) and easy to transport. The amount of fluid needed for the hole is also limited to about 2.5 l/m.

INTRODUCTION

After the successful drilling in 1977/78 at Dome C with the thermal core drill, it appeared that it was not possible to go deeper than 905 m in a dry hole. But before developing a deep core drill working in a fluid filled hole, we thought that a small diameter thermal probe, recovering melt water samples, would be an interesting development.

Stable isotope analyses of this water could provide a continuous record of climatic changes. The aim of the "climatopic" probe is to obtain this climatic record and also to measure, at a later stage, the temperatures in the hole.

Using hot points of the same type as those developed for temperate glaciers (Gillet, 1975) and making runs of up to

6 m, we hope to drill deeper than 3000 m in a single summer season.

EQUIPMENT

Drill Unit

The drill has an outer diameter of 43 mm, weighs 45 Kg and is 15.6 m long. It is composed of five sections having the following lengths: Hot point (0.4 m); Pump and flow measurement section (0.7 m); Melt tank (10.10 m); Electronic and suspension (0.4 m) and the Cable termination section (0.4 m).

Two different types of hot point are used. The first one was developed for temperate glaciers. An insulated nickel-chrome wire is cast in pure silver. These hot points are very efficient and reliable but relatively expensive. We now use high power density cartridges soldered in a copper cylinder (Taylor, 1976). Both types have a power rating of 2250 W at 320 V. To avoid any penetration of water, even under high pressures, a glass-metal sealing is soldered on the cold part of the heating element (Fig. 1).

Suction of melt water is made at 35 cm above the bottom of the hole by a vibration pump. The flow (20-30 l/h) is higher than the production of water (9-11 l/h) to be sure that all the water produced is pumped up. The power delivered to this pump section is high (400 W) and it is difficult to reduce it because of the circulation of cold fluid in the pipes and because we have to start the

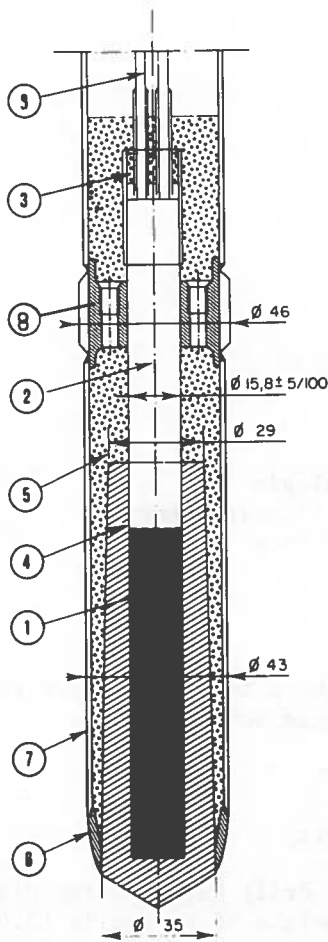


Figure 1. Cross section of the hot point. (1) High power density cartridge; element resistance = 46Ω . (2) Cold part of cartridge. (3) Glass-metal sealing. (4) Copper cylinder brazed to cartridge. (5) Ceramic coating used as thermal insulation. (6) Stainless steel tip brazed onto the copper cylinder. (7) Stainless steel tube. (8) Cooling flange brazed onto the cartridge. The holes are used for setting the ceramic around the copper cylinder. (9) Copper wire used for power conductor.

circulation of water at low temperatures. The flow is measured by a special flow gage while a differential pressure gage indicates the water level in the tank.

The melt tank is made from two stainless steel tubes (40-43 mm diameter) screwed together. To avoid a full refreezing of water, a heating wire located along the axis of the tube gives a power density of 35 W/m . This heat is not sufficient to prevent the formation

of a thick annulus of ice. After each run the tank must be placed in a heated enclosure before all the water is recovered. A floating piston gives an alarm signal when the tank is full.

In order to reduce the size of the cable, the telemetering system uses a bifilar line for four measurements: flow, water level, alarm and suspension. Four low frequency carriers are operated in frequency shift keying mode by four pulse code modulators. The transmitter is located in the upper part of the drill in a 3.5 m long steel tube with a thickness of 6 mm in order to resist the pressures encountered (Fig. 2).

The suspension of the drill on the cable is monitored by the elongation (5 cm) of a spring moving a magnet near a cell using the Hall Effect. Electrical insulation between armor and drill is provided by a Teflon cylinder.

Cable

The cable is 8.9 mm in diameter, is 4000 m long and weighs 1050 Kg. It consists of two outer layers of steel armor and four conductors: two 0.93 mm^2 conductors used in parallel and the armor provide a 7 A RMS current path for the hot points. The surface voltage is about 900 V RMS; two 0.34 mm^2 conductors are used for telemetering.

Power Supply

This unit supplies the 900 V, 7 A power. The voltage is obtained from a three phase 380 V generator by a specially designed inverter, the output voltage from which can be varied from 0 to 1000 volts.

Winch and Tower

The cable is spooled using the "Lebus" system on a Duraluminium drum connected by a chain drive to a gear reducer. A 12 KW, 3 phase, 380 V variable speed motor (120 - 2400 rpm) gives a maximum hoisting speed of 86 m/min. A disc brake is located between motor and gear reducer. For each run, a small hydraulic variable speed motor reducer connected to the main motor by an electromagnetic coupling gives a speed between 2 and 70 m/h. The mast is 11.4 m high and is made of two 250 mm diameter Duraluminium tubes. It is surrounded by four air heated polyethylene tubes designed to receive the melt tanks after each run for recover-

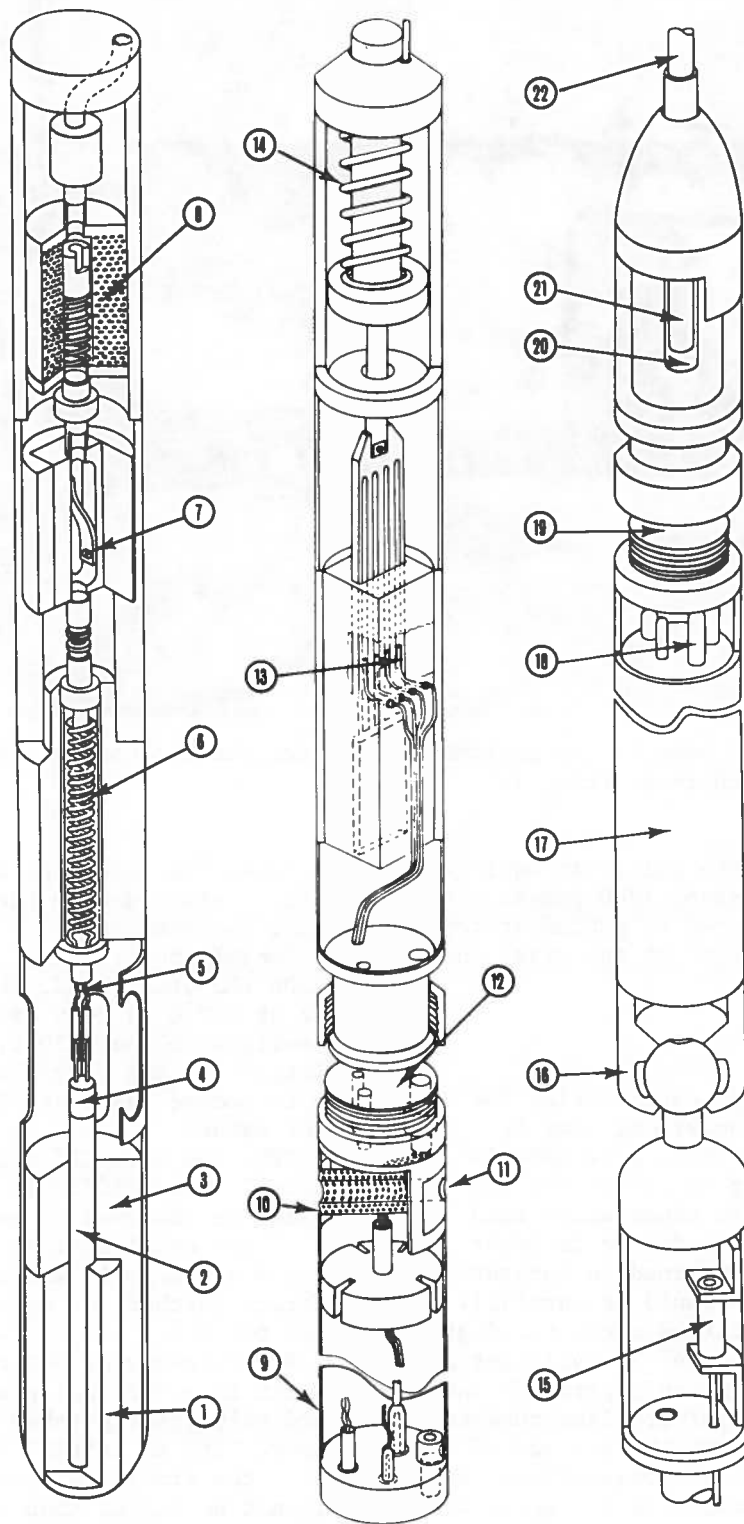


Figure 2. Schematic diagram of the "climatopic" probe. (1) Copper cylinder. (2) Heating cartridge. (3) Thermal insulation. (4) Glass metal sealing. (5) Water suction pipe. (6) Heating wire. (7) Flow gage. (8) Vibration pump. (9) Melt tank. (10) Filter. (11) Drain hole. (12) Connection. (13) Linear slip ring. (14) Suspension spring. (15) Linear transducer. (16) Ball and socket joint. (17) Electronic section. (18) Electrical connections. (19) Connector. (20) Teflon tube for electrical insulation. (21) Cerromatrix cable termination. (22) Armored cable.



Figure 3. General view of the equipment: Inverter (left); Control consol (middle); Winch platform with tower (right).

ing the water.

At the top, the pulley is equipped with a pulse generator (200 pulses per revolution) connected to a counter for determining the depth of the drill in the bore hole.

RESULTS OBTAINED

The drill was tested during the 1981/82 austral summer, at Dome C. Starting from the 180 m hole made in 1978/79 we drilled to 235 m. For the first 28 m we had a penetration rate of up to 5 m/h. This figure is lower than the figures obtained in laboratory tests (8 m/h), and could be partially explained by impurities encountered at the bottom of the hole. To avoid any loss of fluid in the permeable firn, we had installed a 130 m polyethylene tube casing in the hole. With the passage of the drill, small chips of polyethylene were torn off. These particles collected at the base of the hole. The hole then had to be cleaned by coring with a small electro-mechanical drill designed for that purpose as well as for the recovery of small ice cores.

The length of the runs, which is an important parameter for deep drilling, was no more than 4.6 m. This was due to the frequent trouble we had at the beginning with the flow measuring device and with the re-freezing of water in the

melt tank. The flow gage was mounted in a Teflon unit and with the low temperatures, we experienced problems with a reproducible positioning of the sensor.

On the other hand, the viscosity of water at +20°C is very different from the viscosity of DFA at -50°C, giving large variations in the flow. We needed some time to become familiar with these different values.

From 208 m to 217 m it became increasingly more difficult to penetrate the ice. We observed an increasing friction of the drill against the wall of the hole and at 217 m it was not possible to penetrate further. We explain this problem as follows.

The recovery of water in the melt tank set in a vertical position in the heated polyethylene tubes was not satisfactory. With an initial temperature of + 80°C, the final temperature at the top could not be higher than + 15°C and in adverse weather conditions it could be as low as -15°C. The tanks therefore had to be placed in a shelter after each run. The strength of the stainless steel tubes was not high enough, and after a few days of such handling, they became permanently deformed, making it impossible for the drill to pass along the bore hole. Because the bulk of the weight of the drill is located in the upper section (due mainly to the thick electronic tube)

it is not easy to obtain a vertical hole even if the drill is kept carefully in suspension. As the electronic tube is rigid, it probably had difficulty in following the bending radius of the hole without considerable frictional drag. This problem was the main one encountered during the operation. It can be solved by increasing the strength and rigidity of the tubes and by providing an articulation unit below the electronic section.

At 217 m we decided to ream the hole. Restarting from 207 m we advanced very slowly (0.5 to 1.0 m/h) in order to obtain a convenient hole diameter. Friction was immediately reduced and at 220 m we could increase the penetration rate to 2 m/h keeping friction to reasonable levels.

At this depth, we had solved the other problems previously observed concerning mainly hot points, the pump, flow measurement, and the heating of pipes. Then, we could get regular runs and reproducible figures before total refreezing of water in the tank. Usually the drilling would occupy about 45 minutes. This figure is appropriate if the penetration rate is 8 m/h. It could be slightly increased by a better heating of the lower part of the tank.

At 5 m/h we obtained 10 l/h of water. The water level in the tank was not measured because of a breakdown of the differential pressure gage, which was not suited to these working conditions. A better separation between water and DFA must also be achieved.

ELECTRO-MECHANICAL DRILL

With an OD of 43 mm and a length of 3 m, this small drill is designed to produce cores up to 50 cm long. A 2 Nm torque at 93 RPM is provided by a 115 V DC motor reducer. The chips are circulated by a turbine pump operated by a 75 V DC motor and stored in a special filter compartment.

This drill was designed to be used periodically in conjunction with the main climatopic probe. In this way, ice core may be obtained at desired depths.

This drill worked without any major problems, but the core length must be increased from the present 20 cm.

LOGISTICS

The equipment, including the generator, weighs 8000 Kg in packing cases.

To this must be added the DFA needed for the generator (about 4 l/h) and the drilling fluid (about 2.5 l/m). This fluid is a mixture of DFA and Freon (F 11).

ACKNOWLEDGMENTS

We would like to thank the U.S. National Science Foundation for its essential logistical support in the field at Dome C. We also thank the Terres Australes et Antarctiques Françaises and the Expéditions Polaires Françaises for their financial and logistical support.

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HOT WATER DRILLING IN ANTARCTIC FIRN, AND FREEZING
RATES IN WATER-FILLED BOREHOLES

Bruce R. Koci
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0200

Abstract

Hot water drilling systems are suitable for applications in which the objective is to gain rapid access to a glacier, ice sheet or ice shelf for seismic shooting, installing temperature sensors, access hole studies or retrieving stuck core drills. The Ross Ice Shelf Project (RISP) hot water drilling at J-9 showed that the decrease in water temperature at the nozzle was $1^{\circ}\text{C}/30\text{ m}$ ($1.8^{\circ}\text{F}/100\text{ ft}$) of depth. The boiler was rated at 2.5×10^6 watts. It produced 320 l/m of water heated from 2°C to 98°C (1.75×10^6 watts). The success of a smaller hot water system (150 kW) used by PICO in 1979-80 at Dome C, Antarctica, in ambient temperatures of -40°C illustrated the speed and reliability possible under extreme environmental conditions.

Browning Hot Water Drill

The Browning hot water drilling conducted in 1978 as part of the Ross Ice Shelf Project (RISP) at J-9 demonstrated that access holes could be drilled rapidly to depths of 420 m. The drill consists of a single 2.5 megawatt boiler, heat exchanger, downhole pump, booster pump and reels of hose with a 6-m long 5-cm diameter pipe and nozzle (Browning et al., 1979). By using water created and stored in an in situ water well it was not necessary to provide surface storage for water during drilling (Figures 1-3). This drill was used in 1978-79 to drill three access holes through 420 m of ice at the RISP camp J-9.

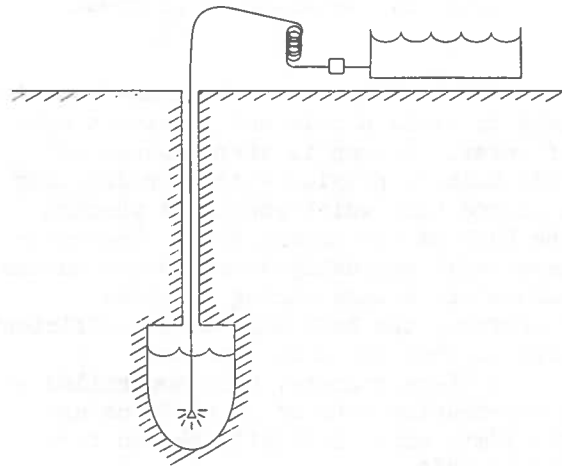


Figure 1. Development of water well using surface water

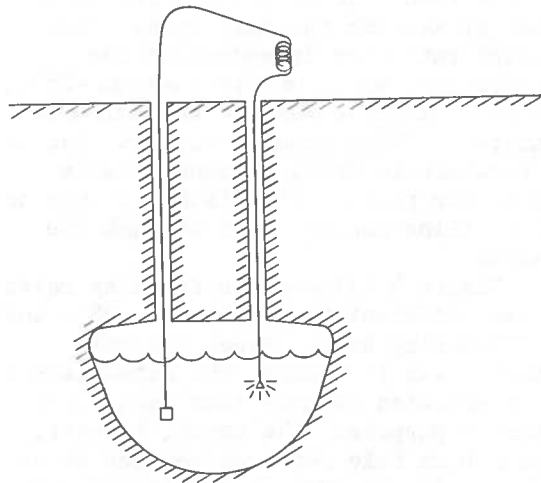


Figure 2. Drilling of second access hole

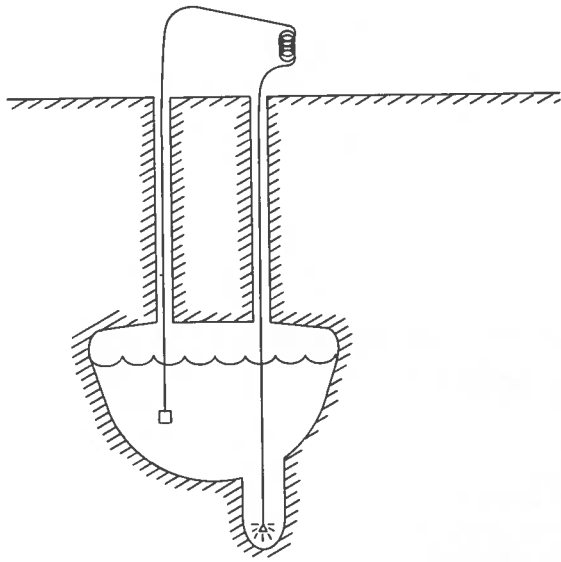


Figure 3. Drilling in progress

First, water from a storage tank is used to drill a hole and provide a bulb of water. A pump is then lowered into this bulb to provide water for drilling a second hole which continues through the bulb as the access hole. The water level will gradually decrease due to the volumetric change during melting. Therefore, the bulb must be of sufficient size to keep the pump immersed.

A 76-cm diameter hole was drilled at a penetration rate of .7 m/min using 320 l/min water initially heated from 2°C to 98°C.

During drilling, the rate of decrease in water temperature at the nozzle was recorded as 3.3°C/100 m depth. Freezing rates began at 10 cm/24 hours, decreasing to less than 5 cm/24 hours after three weeks of keeping the hole open. These closure rates are dependent on ice temperature, which in this case was -28°C, and to a lesser extent on initial hole diameter. These results suggest that it is possible to drill to considerable depths for placing thermistor strings or for drilling access holes through ice shelves.

Figure 4 illustrates freezing rates at two different temperatures (-28°C and -17°C) during RISP. Since the hole diameter was irregular, the rates cannot be interpreted as more than values for estimate purposes. We noted, however, that a 30 cm hole required between three and four days to freeze completely and that measurements made with ultrasonic detectors gave results within 5 mm of

those measured with the caliper.

Calculations of freezing rates with a moving boundary are difficult and depend on many assumptions. Those made by Yen and Tien (1976) suggested complete freezing of a 30 cm hole in eight hours. The heat balance integral method of Lunardini (1981) gives results within 25 percent of these measured.

PICO Hot Water Drill

The success of a smaller hot water drill system designed by PICO and used at Dome C, Antarctica, showed that in ambient temperatures of -40°C hot water drills could be used reliably to drill shot holes and recover stuck ice core drills to depths of 70 m. The PICO hot water drill system is a noncoring shallow-depth drill consisting entirely of off-the-shelf components. The drill consists of three Malsbary oil-fired water heaters (two Model 21-H and one Model 221-H) used in varying combinations to melt the required snow in a 2250 l reservoir tank, and to heat the meltwater for drilling. The heated water in the tank was pumped through a Synflex hose and out through a nozzle to melt the hole. For use at high altitudes, the oil burner nozzles were changed, reducing the fuel consumption rates to 7 l/hr and 21 l/hr, respectively.

At Dome C during late December 1979 through early January 1980, the PICO hot water drill was used to provide shot holes of depths between 15 m and 60 m for the University of Wisconsin-Madison Geophysical and Polar Research Center's seismic program (Kuivinen et al., 1980). PICO drilled a total of 37 shot holes at 17 sites over a 30-km area, providing 1085 m of holes in ten days of drilling. Water pools in these holes at about half the firn-ice transition depth, so many of the holes at Dome C were unusable below 40-45 m. The Geophysical and Polar Research Center seismic investigations included a wide-angle reflection profile, a P-wave refraction profile, two large separation refraction shots and surface wave recording.

Upon completion of the drilling in support of the seismic program, PICO used the hot water drill to melt free the NSF-Swiss shallow drill stuck at 65 m depth during the previous season. The drill was recovered intact, and was retrograded to Lincoln for overhaul.

It was found that only 1135 l of water were needed to drill a 60 m hole.

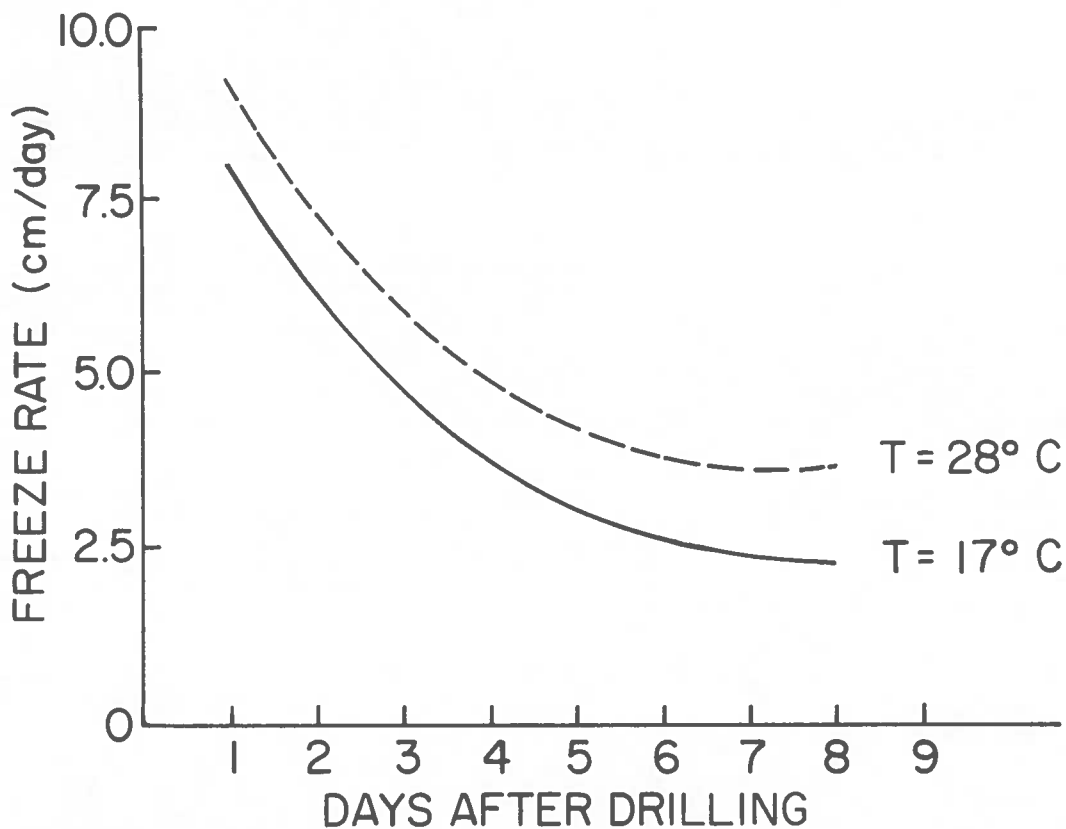


Figure 4. Freezing rate as a function of time for two different temperatures (depths) in the Ross Ice Shelf.

By raising the water in the tank to 5°C it was possible to deliver water to the drill head at 95°C (7°C above boiling) because of the back pressure at the nozzle. Water delivery was at the rate of 32 l/min with 160 kW used to heat the water during the drilling stage. Drilling rates ranged from 360 m per hour for the top 10 m of the firm to 120 m per hour to reach 60 m with a minimum hole diameter of 7.6 cm. Cycle time for each 60 m hole was about 2.5 hours, which allowed us to drill holes at two sites per day.

This work was supported by the National Science Foundation under contract DPP74-08414 with the University of Nebraska-Lincoln, Polar Ice Coring Office.

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A HOT WATER DRILL FOR TEMPERATE ICE

Philip L. Taylor, U. S. Geological Survey

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:

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

where:

		<u>Metric units</u>	<u>English units</u>
\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	1.5×10^4

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

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_j^5	0.786	7.42×10^{-3}

head loss across the nozzle

5.5 bar	= 56 m	185 ft
(80 psi)	(of water)	

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

$$1 \text{ psi} = 0.433 \text{ ft of water}$$

$$1 \text{ bar} = 10.2 \text{ m of water}$$

$$1 \text{ kPa} = 0.102 \text{ m of water}$$

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:

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

$$\text{rearranging, } \dot{m} = K_1 \frac{(\bar{d})^2 R}{T_2}, \text{ with } K_1$$

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

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:

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

$$\text{and since } \ln \frac{T_1}{T_2} = \frac{(k/t) \pi d_m l}{\dot{m}}, \quad \eta$$

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	$\frac{k}{\text{metric units}}$	$\frac{k}{\text{English units}}$
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 $2-5 \times 10^4$, 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

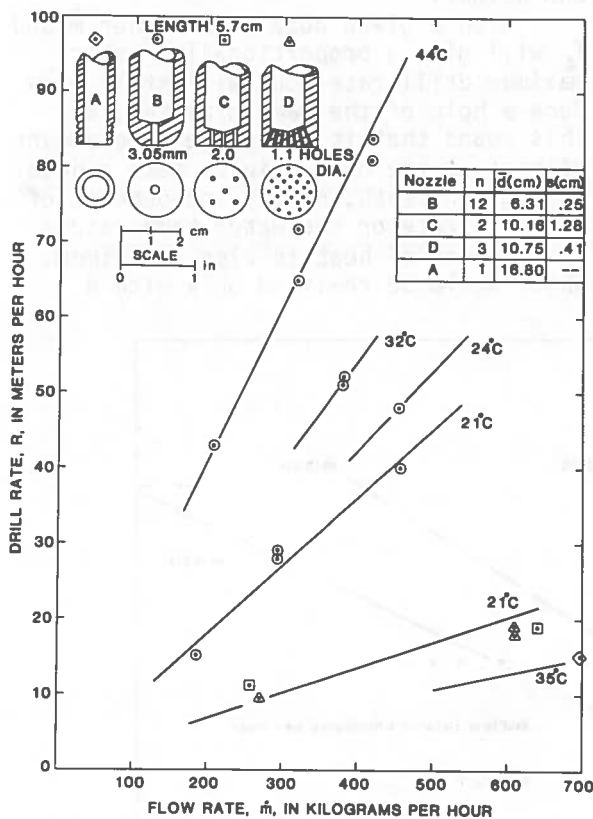


Figure 1. Block Ice Tests. Number of data points, n , with lines of slope \bar{d} calculated from equation 1 at the nozzle water temperature indicated; s , the standard deviation of each set. Test nozzles made of brass. Drill rate proportional to flow rate.

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.

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_w . This produces a bore-hole of smaller average

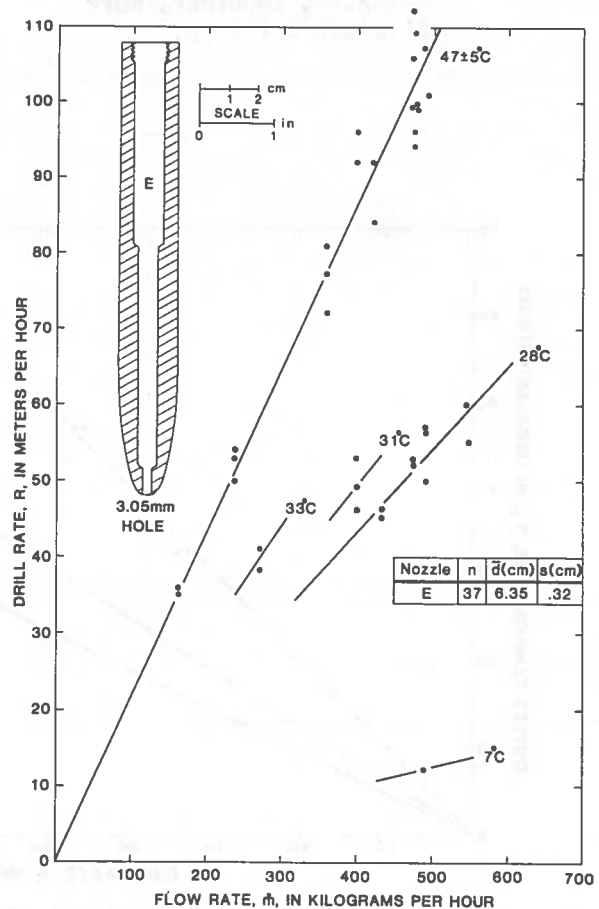


Figure 2. Test results for a longer nozzle E.

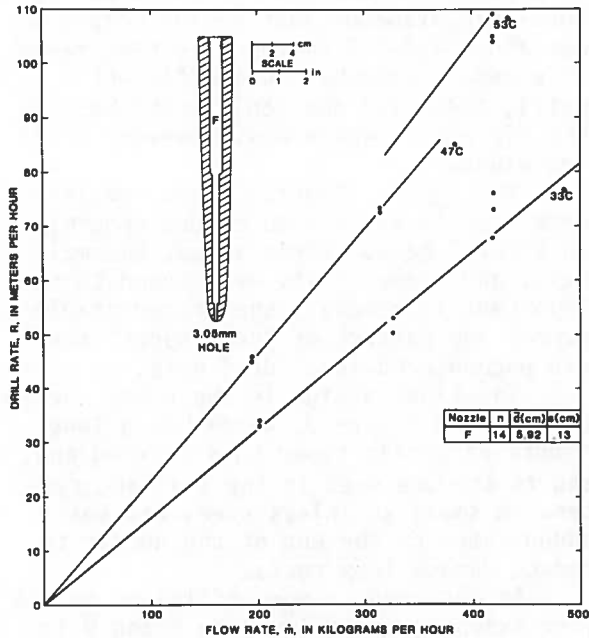


Figure 3. Test results for a larger and more pointed nozzle F. Both \bar{d} and s have smaller values indicating smoother, more efficient drilling.

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

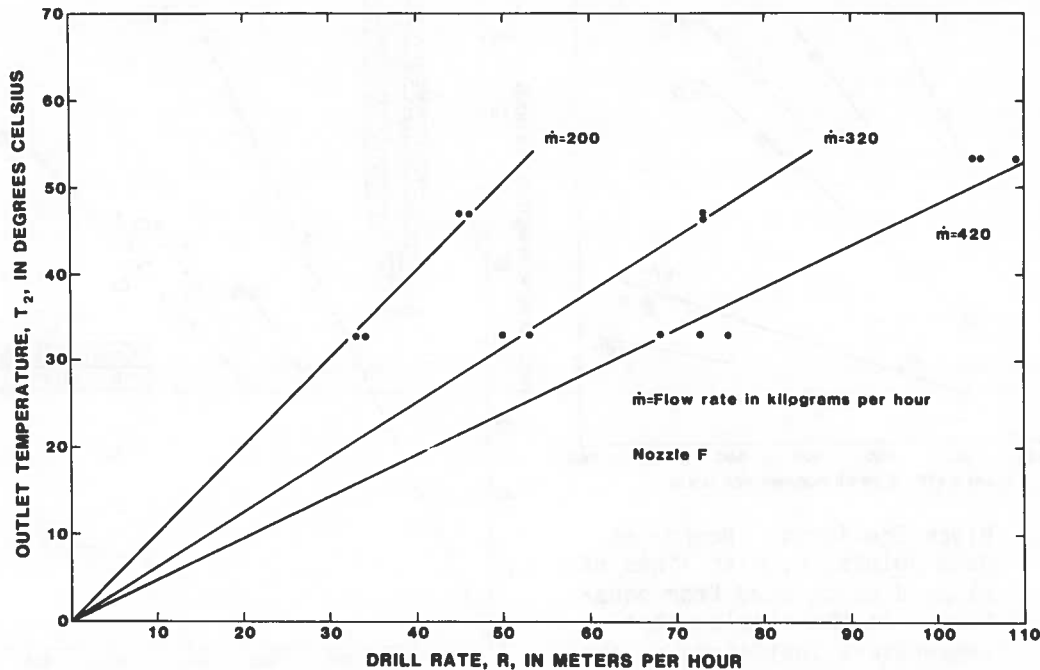


Figure 4. Data of figure 3 for nozzle F, with slope of lines $\bar{d} = 5.92$ cm at the mass flow rates indicated. Drill rate proportional to outlet water temperature, T_2 .

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, $1 - \eta$, lost through the walls of the hose, which only serves to increase the bore-hole diameter beyond \bar{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 \bar{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 38°C (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 additional 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 m³ with an overhead array of spray nozzles and recirculated hot water from a heater and pump separate from the drill system. Snow was shoveled into the tub, and the accumulated

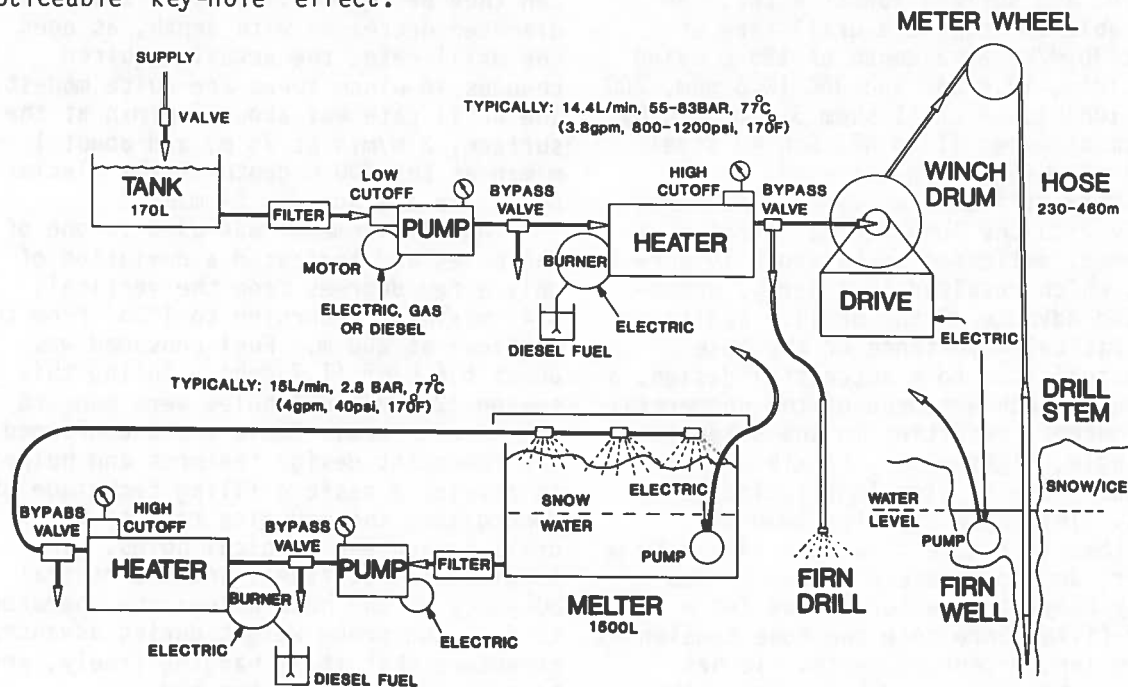


Figure 5. Block Diagram of the Drilling System. Additional equipment notes on the facing page.

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 unforeseen 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 continue 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 com-

mun.). 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.

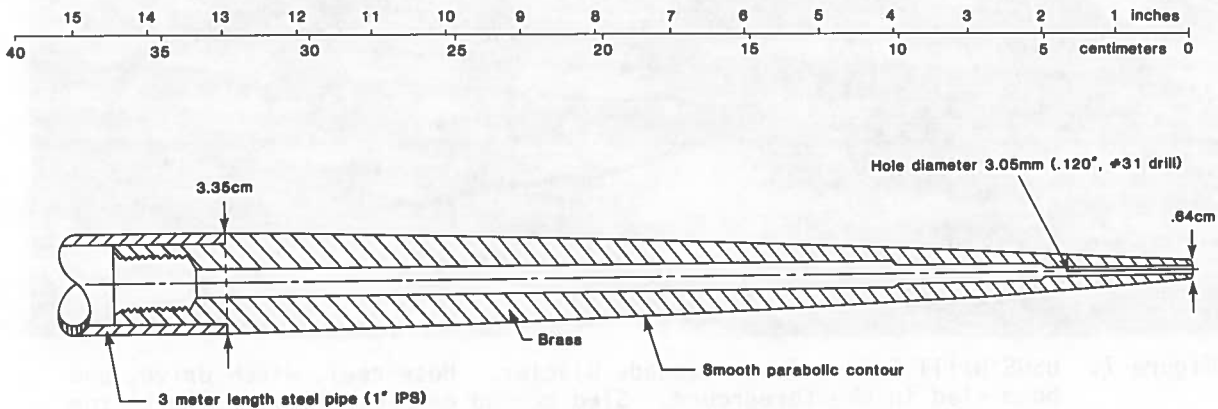


Figure 9. Drawing of the nozzle shown in figure 8.

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.

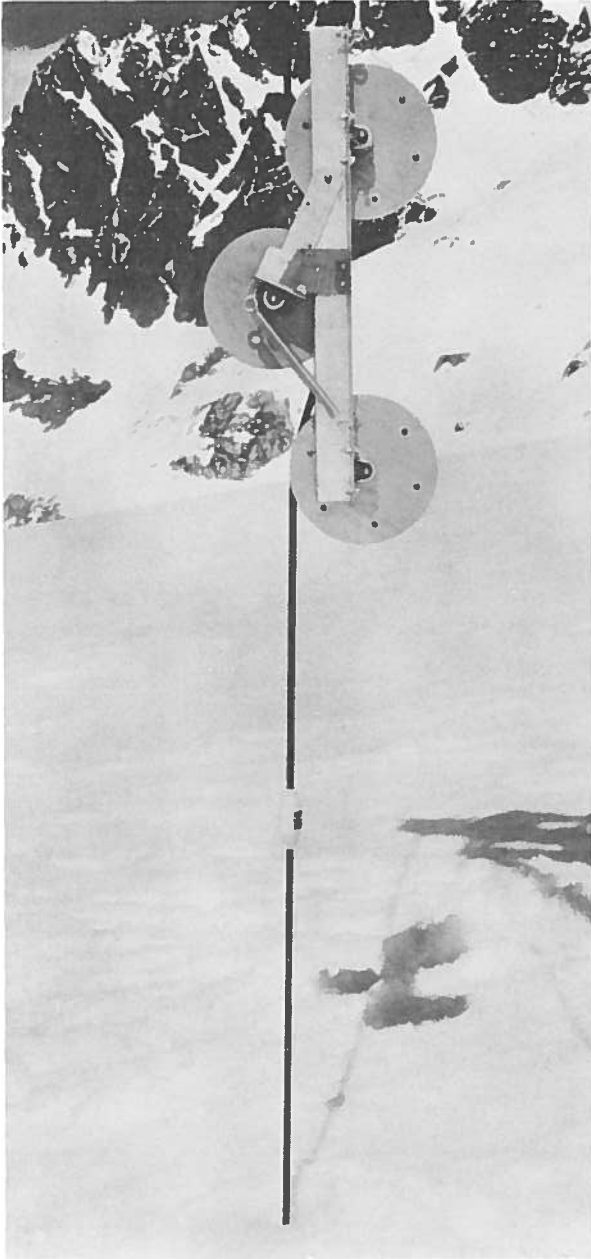


Figure 10. Hose Tensiometer, which can be easily installed and removed. A spacer has just been installed on the hose. Drill rate about 1 m/min.

Acknowledgments

This work was supported by the Glaciology Project Office, Water Resources Division, U.S. Geological Survey. I wish to extend thanks to Charles Raymond and Richard Metcalf, University of Washington, for their support and assistance in the early work on Blue Glacier; to Steven Hodge, USGS, for his many valuable ideas and contributions (the design of the sleds in figure 7 for example); to both Steve Hodge and Carolyn Driedger, also of USGS, for their dedicated efforts during the many field trips; to the numerous helpful assistants; and to Barclay Kamb, California Institute of Technology for providing his valuable field experience on Variegated Glacier, and the use of his photograph in figure 6.

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AN IN-SITU SAMPLING THERMAL PROBE

B. Lyle Hansen and Leendert Kersten
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0200

Abstract

Philberth's thermal probe concept and Aamot's pendulum steering technique have been incorporated in a new design which passes a portion of the meltwater formed at the tip of the probe through its interior where various parameters such as conductivity can be continuously monitored in high pressure cells. The telemetry system and probe design will permit the addition of other in-situ measurements.

A simple DC measurement system provides precision measurement of the ice temperature and changes in the inclination of the probe during freeze-in periods at selected depths in the ice sheet.

Introduction

In 1979, the Polar Ice Coring Office (PICO) undertook the development of an in-situ sampling thermal probe the design of which would: minimize the possible occurrence of the difficulties encountered by previous probe users, include a telemetry system to permit measurements while advancing under power, provide means for making various measurements on the meltwater flowing from the tip of the probe through high-pressure sample cells within the probe, and provide a simple DC measurement system and the transducers necessary to measure changes in the orientation of the probe due to the flow of the ice sheet during freeze-in periods while the cooling curve of the probe is being

measured.

The probe is pendulum stabilized; its center of gravity is below the 16.5 cm diameter upper hotpoint which controls the advance rate (Figure 1). The lower hotpoint and the body of the probe have a diameter of 12.7 cm. The overall length is 3.45 m and the weight of the probe in air is 150 kg.

The lower 2.11 m segment of the probe is a hermetically-sealed, thick-walled, non-magnetic stainless steel chamber at atmospheric pressure which is designed to withstand an external pressure of 5×10^7 N/m² or "pascals" caused by the overburden of 4000 m of ice plus a peak over pressure which exists temporarily during the refreezing of the meltwater. This chamber contains the two hotpoints, transducers, high-pressure sample cells and the telemetry equipment.

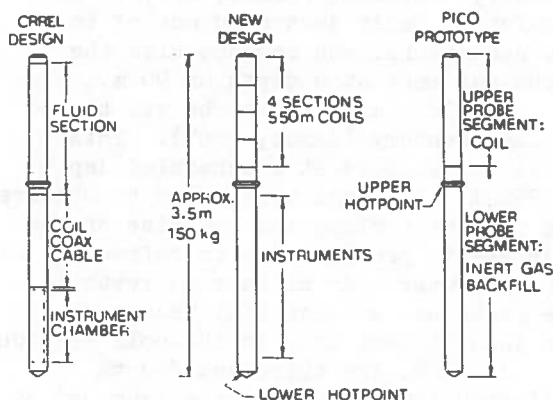


Figure 1. Thermal probe designs

The upper 1.32 m segment of the probe contains about 3 km of miniature coaxial high-voltage cable tested to withstand 3000V DC immersed in water; this segment is open to the ice/water environment.

Most of the exterior cylindrical surface of the probe is covered with a Nichrome V ribbon heating element sandwiched between fiberglass-reinforced epoxy layers. The purpose of this heating element is to melt the ice around the probe when starting up after a freeze-in period. It provides a power density of 0.3 watt/cm² of exterior surface area. Tests have shown that it melts the probe free in ice of -40°C temperature in approximately one hour, the interior chamber temperature at melt-out being about 20°C.

History

In 1962, Karl Philberth (1962) described the concept of he and his brother Bernhard for a thermal probe to measure the temperature inside of an ice sheet. The outstanding characteristic of this probe was that the wire for the transmission of electrical power to it and signals from it payed out of the advancing probe and became fixed in the refreezing meltwater above it.

In 1962, Philberth's (1964) concept of a mercury steering-ring to stabilize the vertical course of the thermal probe was successfully tested at Jungfrauoch, Switzerland.

In 1964, the development of the Philberth thermal probe was undertaken at USA Cold Regions Research and Engineering Laboratory (CRREL) with the assistance of K. Philberth.

In 1965, the first Philberth probe built at CRREL was tested at Camp Century, Greenland (Aamot, 1967). An insulation fault destroyed one of the two conductors, and contact with the probe was lost at a depth of 90 m.

In 1966, a second probe was tested at Camp Century (Aamot, 1967). This probe was stopped at a scheduled depth of 259 m. Readings were taken to observe the rate of cooling and the rise of the hydrostatic pressure due to refreezing of the meltwater. An attempt to restart the probe was unsuccessful because there was insufficient heat in the coil section.

In 1968, the third and fourth Philberth (1976) probes were launched at Station Jarl-Joset, Greenland. The cartridge heaters in the third probe

short-circuited at a depth of 218 m, and again in the fourth probe at a depth of 1005 m. Temperatures were measured at depths of 218, 615 and 1005 m. The fourth probe was successfully stopped at 615 m, allowed to freeze-in for the temperature measurement, and then restarted on its way.

Two thermal probes with pendulum vertical stabilization have been launched in Antarctica (Aamot, 1970).

In 1971, a CRREL pendulum probe was launched at South Pole Station by John Rand (1971). It failed at a depth of 6 m, probably because the coil was inadvertently overheated by operating at too high a power level in the porous firn.

In 1973, the Australians (Morton and Lightfoot, 197-) launched their thermal probe at a site 80 km south of Casey Station where it reached a depth of 112 m when it failed, probably due to inadequate insulation on the stepping switch. The temperature at that depth was measured.

Design Features

To minimize the possible occurrence of the difficulties encountered by previous probe users, PICO undertook the analysis and design of a hermetic seal for the cartridge heaters, which previously were not hermetically sealed and could have caused moisture to enter in the insulation around the heating element and/or the oxidation of this heating element itself, resulting in a reduction of the wire diameter.

Two approaches were investigated: (a) hermetically-sealed cartridges were fabricated and tested with very satisfactory results -- their production was difficult to achieve and very expensive; (b) normal off-the-shelf cartridges were purchased -- after insertion in the hotpoints, these assemblies were baked out at 120°C for approximately one hour prior to final assembly of the lower segment of the probe. Since the interior of the probe is evacuated and refilled with an inert gas the heaters need not be hermetically sealed. Test results have indicated a sufficiently acceptable performance.

The cartridge heaters in the upper and lower hotpoints are operated at 50 percent of their rated wattage. At a maximum operating voltage of 1325V DC and a current of 4.07 amperes, the total heating power of 5400 watts is so

divided that 1350 watts are dissipated in the upper hotpoint and 4050 watts in the lower hotpoint.

The entire 2.11 m lower segment of the probe is hermetically sealed by a combination of a U-type Variseal and a pair of O-rings; this provides redundancy but also the needed assurance of adequate sealing (Figure 2).

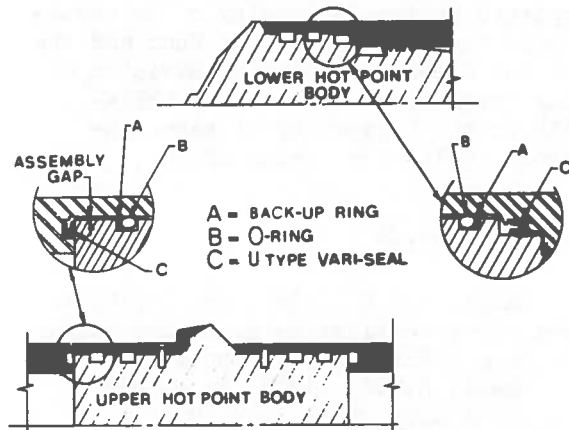


Figure 2. Hermetic sealing method of the instrument chamber

The miniature coaxial high-voltage cable consists of a solid center conductor insulated with an extruded copolymer of ethylene and tetrafluoroethylene (DuPont's TEFZEL) covered with a braided silver-plated outer conductor.

The center and outer conductors are dead-soft annealed copper. This should permit a 20 percent elongation due to movement of the ice before the cable ruptures.

The dielectric strength is tested by immersing the complete coil in tap water at room temperature and applying a difference of 3000V DC for four hours between the center conductor (cathodic = negative) and the surrounding water -- any breakdown constitutes a failure.

The specified cable diameters and values measured on a sample are shown in Table 1. The maximum DC resistance of the center and outer conductor at 20°C are 0.0334 Ω /m and 0.0295 Ω /m, respectively. The maximum specified loop resistance of 0.0629 Ω /m exceeds the 0.057 Ω /m measured on a 50-m sample.

The characteristic impedance, Z_0 , and propagation constant, γ , were calculated at frequencies of 100, 1000, 10,000 and 100,000 Hz to confirm the capability of transmitting a continuous stream of data to the surface while advancing the probe under power.

The telemetry system is powered by a string of Zener diodes in series with the heating elements. The DC output voltages of the transducers are converted into pulses in the audio frequency range. These variable-frequency pulse trains are sequentially transmitted over the coaxial cable to the surface monitoring station which consists of a Hewlett-Packard 1222A oscilloscope and 5316A universal counter, a Fluke 1720A controller-computer, a Fluke 2020A printer and signal processing electronics. The data is gathered, analyzed and then stored on floppy disks (5 $\frac{1}{4}$ -inch diameter) for future use.

This probe, like all of its predecessors, contains a rotary selector switch, but the significant difference is that this switch has a much higher dielectric strength of 3000V DC and a current carrying capacity of 17 amperes. The switch is actuated by reversing the polarity of the DC voltage feeding the coaxial cable. Its use permits: (a) the application of power to any one or selected combination of heating elements, (b) measurement of the resistance of the heating elements or various thermistors, (c) measurement of the voltage or charging of the battery pack used to energize the transducers for DC measurements, (d) measuring the

Table 1. Specification of Miniature High-Voltage Coaxial Cable with TEFZEL Insulation

	<u>Specified Cable Diameter</u>	<u>Measured Diameter</u>
Center Conductor	0.805-0.823 mm (0.0320 + .003 - .0004 inch)	0.823 mm (0.0324 inch)
Over Insulation	1.245-1.321 mm (0.0505 \pm .0015 inch)	1.245 mm (0.0490 inch)
Overall	1.727-1.829 mm (0.070 \pm .002 inch)	1.748 mm (0.0688 inch)

DC voltage outputs of the inclinometers, compass and pressure transducers.

The pressure transducer, a Schaevitz P763-0001A, measures the pressure of the meltwater. A conductivity cell of in-house design measures the conductivity of the meltwater as it advances through the probe.

The inclinometers, Schaevitz LSRP-14.5, are calibrated at -30°C for operation over the range of 0°C to -55°C . They are in a 90° x-y axis offset stack with a Z-axis alignment.

The compass is a Norwegian-made Aanderaa Model 1248 rotating, permanent magnet unit.

The coil section which contains the coaxial cable, unlike all previous probes, is placed atop the upper hotpoint (Figure 1). The PICO prototype thermal probe uses a CRREL coil section, but future probes will use a customized coil section. This consists of individual sections, each of which contains 550 m of coaxial cable and is 29.2 cm long. The advantage of the sectioned coil segment is the reduction in cable cost and winding cost. A specially-designed, collapsible mandrel is available for the orthocyclic winding of the coaxial cable (Lenders, 1962).

Performance

The performance of the prototype probe has been tested at the PICO laboratory in ice conditions ranging from -50°C to -25°C .

The penetration rate in ice at a temperature of -25°C is 1.6 m/hr. The penetration rate is controlled by the upper hotpoint. The calculated power distribution of $1/4$ to the upper hotpoint and $3/4$ to the lower hotpoint ensures the proper vertical pendulum steering of the probe. The Australian probe also utilizes a similar power distribution (Morton and Lightfoot, 197-).

The CRREL coil to be used on the prototype was frozen in ice at a temperature of -40°C . The coil was freed after one hour at a current of 4 amperes.

The wall heaters on the exterior of the probe's instrument and coil sections are designed to provide sufficient heat for a complete melt-out after the freeze-in period. The designed flux density of 0.3 watt/cm^2 , at a current of 3 amperes, melts the probe free from the -40°C ice in approximately one hour.

Tests which must be completed

before launching the prototype include: (a) overall systems pressure, (b) flowrate of meltwater through the probe when penetration is controlled by the upper hotpoint, and (c) calibration of the conductivity cell.

Acknowledgements

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PRELIMINARY RESULTS OF DEEP DRILLING
AT VOSTOK STATION, ANTARCTICA 1981-82

B.B. Kudryashov, The Leningrad Mining Institute,
V.K. Chistyakov and Leningrad, U.S.S.R.
E.A. Zagrivny
and
V.Ya. Lipenkov The Arctic and Antarctic Research
 Institute, Leningrad, U.S.S.R.

ABSTRACT

A description is given of the deep thermal core drill being used at Vostok Station, East Antarctica. A report on the drilling progress is also given.

INTRODUCTION

In 1980, at Vostok Station, East Antarctica, drilling of a new, deep bore-hole was begun. Special low temperature liquid was developed and used to fill the bore hole to maintain its wall stability during drilling and subsequent logging operations.

The main objective of the first stage of deep drilling at Vostok Station in 1980-81, was the full scale trials of new equipment and procedures for thermal coring in liquid filled holes in very cold ice. A new thermal, cable suspended drill, designed at the Leningrad Mining Institute, was tested. It was built as a mobile rig and transported to Vostok Station by sled-tractor train.

DESCRIPTION OF THE EQUIPMENT

The mobile drilling installation (PBU-2) is a heated drilling facility with a heated metal tower extending 7 m above the roof of the building. The rig is sled mounted. In the shelter, there is an electrically driven hoist (10 kW), an electrical control panel for the drills and winch, 2 diesel electric generators (16 kW each), a water heating unit as well as lighting and heating equipment.

There are three electro-mechanical cables.

The KEMMP-6 is 22 mm in diameter and weighs 1400 kg/km. There are three copper cored power cables (each core is 4 mm² in cross-sectional area) and three signal cores (each 0.75 mm² in cross-sectional area).

The KG-7 cable is 16.5 mm in diameter and weighs 890 kg/km. There are seven power conductors (each 2.5 mm² in cross-sectional area).

The KG-2 cable is 11.5 mm in diameter and weighs 400 kg/km. It has a central copper conductor 4 mm² in cross-sectional area.

Depending on the power rating of the separate units and the cable losses, the heater units are operated at 40-1000 V AC or DC, at 50-2500 Hz.

Drilling of the first 112 m was carried out using a TELGA-14M core drill (Korotkevich and Kudryashov, 1976) designed for coring 180 mm ϕ dry holes.

Drilling beyond this depth was carried out using the TBZS-152M core drill (Fig. 1). A hydrocarbon based liquid, the concentration of which was regulated according to the temperature, was used to fill the hole below the firn-ice transition. It provided the required hydrostatic pressure to inhibit hole closure.

The annular heater of the core drill operates at 3.0-3.5 kW, producing a drilling rate of from 2.0-2.5 m/h. An average run is 2 m. Mean core and

hole diameters are 110 mm and 154 mm respectively.

Although perfect balance of the ice pressure is unlikely, no obvious difficulties resulting from any hole closure at pressures of from 2 to 4 MPa were experienced. All the systems and units of the drill (the heater, the melt water sections core lifters and pressure gages) proved reliable and efficient.

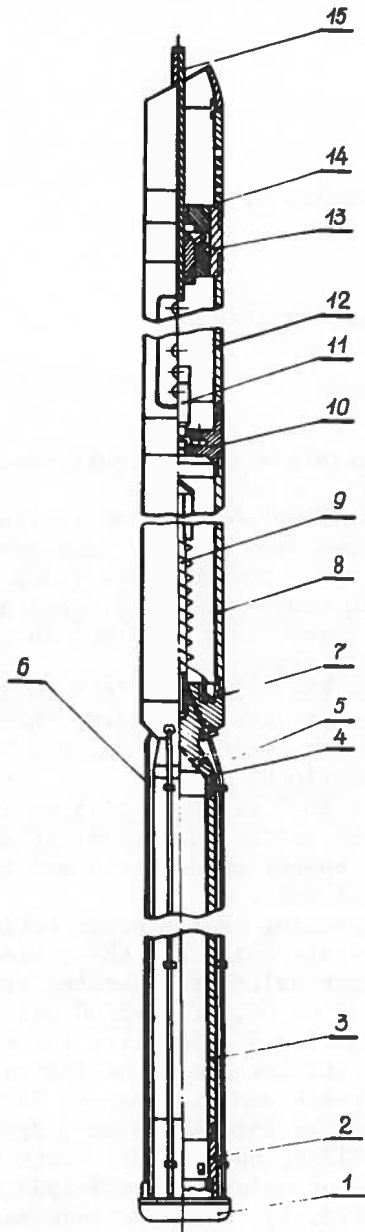


Figure 1. The TBZS-152M thermal core drill. (1) Heater ring (2) Core lifter (3) Core barrel (4) Drain adapter (5) Water pipes (6) Heater power cable (7) Water heater (8) Tank (9) Water pipe (10) Pump adapter (11) Pump (12) Electrical section (13) Cable termination (14) End cap (15) Electro-mechanical cable.

During drilling, a number of new techniques were developed and tested. These included an automatic down winching system, a system thyristor control of the heater power and new cable construction and termination.

Early in 1981, after a depth of 1500 m was reached, the drilling continued using the TBS-112 HF core drill with a high frequency power transformation which significantly reduces cable power losses and allows more power to be available for melting ice (up to 5 kW). The hole diameter was reduced to 112 mm. The drilling rate of the new drill increased to 3.5 to 4.0 m/h and early in 1982, the Vostok N/3G hole was 2000 m deep.

This hole was logged for temperature, bore hole geometry and some physical and mechanical properties adjacent to the hole wall.

Core recovery was 99.9 % and quality was high.

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EQUIPMENT AND TECHNOLOGY FOR
DRILLING IN TEMPERATE GLACIERS

V.A. Morev, V.A. Pukhov
and V.M. Yakovlev
and
V.S. Zagorodnov

The Arctic and Antarctic Research
Institute, Leningrad, U.S.S.R.

The Institute of Geography, U.S.S.R.
Academy of Sciences, Moscow

ABSTRACT

Three drill units suitable for drilling in temperate ice are described. They are an electro-thermal corer, an electro-thermal spike and a hydro-thermal drill. The function and field use of these units is briefly discussed.

INTRODUCTION

Many mountain glaciers in mid latitudes and some glaciers on the Arctic Islands may be considered as temperate. The temperature below a surface active layer is at or close to the melting point. During the summer, an intensive melting occurs and free water may be encountered both at the surface and in the body of the glacier.

The thickness of these glaciers is mainly between 100 m and 500 m, but occasionally thicknesses of 800 m or more may be encountered.

In the accumulation zone, there may be thick firn layers while in the ablation zone, moraine and other deposits may be found in various concentrations.

DESCRIPTION OF DRILL UNITS

The Electro-thermal Core Drill ETB-1

An electro-thermal core drill, model ETB-1, (Fig. 1) was developed for core drilling in temperate ice (Morev, 1972). It consists of an annular bit or shoe attached to the lower end of a core barrel, to which are attached a set of

core grippers. At the upper end, there is an end cap assembly and a spring loaded cable termination.

The ETB-1 differs from the ETB-3 unit (Morev, 1974) by the absence of the piston, the double core barrel and the filler tube.

After the drill has been lowered into the hole, the power is supplied to the drill heaters, causing melting of the ice there. The advance rate of the cable is controlled by the tension on the cable that is measured by means of a block balance. The power load on the drill heaters is controlled by means of the voltage controls on the operators panel. When the bore hole becomes contaminated with debris, the speed of drilling is seen to be reduced. To restore the speed, it is necessary to clean the bore hole bottom. To do this, a conical nosed heater unit is lowered to the base of the bore hole on the next run, and a conical hollow is melted into the ice. The debris then collects in this conical space and most of it may be brought up still trapped at the top of the next core. During such coring operations, the hole is usually filled with melt water which prevents hole closure.

The drill has the following specifications:

Outer diameter of shoe,	108 mm
Inner diameter of shoe,	84 mm
Bore hole diameter,	112-120 mm
Core diameter,	78-82 mm
Length of drill,	1.5-3.5 m

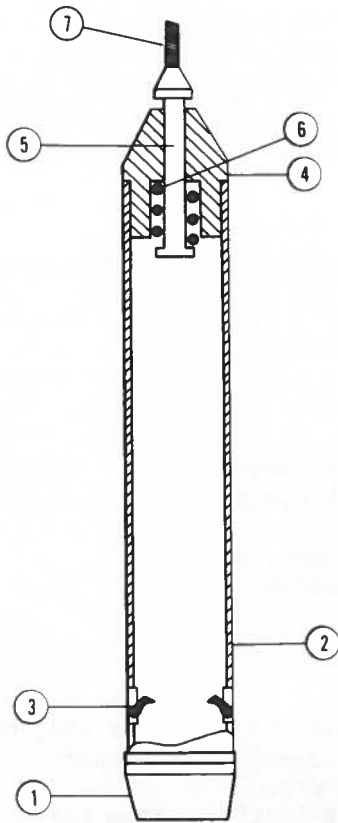


Figure 1. ETB-1 electro-thermal core drill. (1) Heater shoe. (2) Core barrel. (3) Core grippers. (4) End cap assembly. (5) Cable termination unit. (6) Spring. (7) Electro-mechanical cable.

Length of core,	1.0-3.0 m
Drill weight,	15-40 kg
Power intake,	1-3 kW
Drilling rate,	2-6 m/h

The electro-mechanical cable is a single core, armored type with a diameter of 8.6 mm. Power is transmitted through the core and the armor. A manual or electric drive winch is used to feed the cable which is normally 500 m long. For this depth drilling, a generator of about 4 kW is sufficient.

The Electro-thermal "Needle" Drill

This unit, shown in Fig. 2, was developed for hole drilling without core recovery. It consists of a conical heater bit attached to a pipe by means of a coupling nut and connector. To the upper end of the pipe is attached the cable termination assembly which is surrounded by the spring loaded hole centering device. Power is transmitted through the

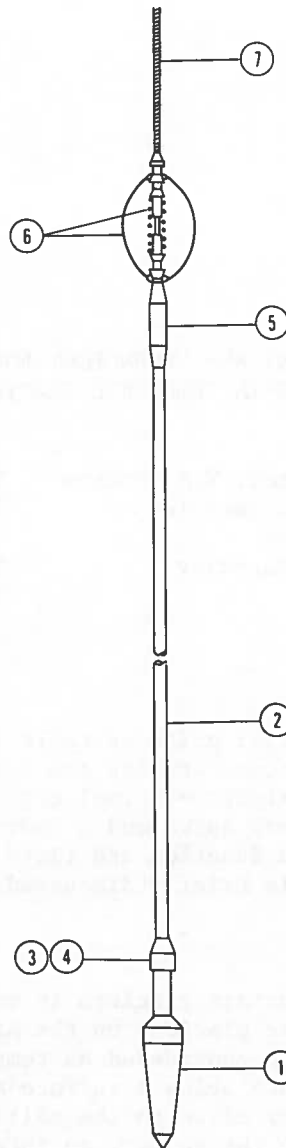


Figure 2. Electro-thermal "Needle" drill. (1) Conical heater bit. (2) Central pipe. (3) Coupling nut. (4) Connector. (5) Cable connector assembly. (6) Spring loaded hole centering device. (7) Electro-mechanical cable.

core and the armor of the cable. If clay and sand accumulate significantly at the base of the hole, the heaters may over heat and burn out.

The drilling rates should be monitored constantly, and the heater power varied in direct relation to the drilling speed. The tension in the cable is controlled by means of a block balance.

The drill has the following specifications:

Drill bit diameter, 40 mm

Bore hole diameter, 42-55 mm
 Length of drill, 1.5-2.0 m
 Drill weight, 5-7 kg
 Power intake, 1-3 kW
 Drilling rate, 6-18 m/h

Core and bore hole drilling in temperate glaciers of the Caucasus, Pamirs, Polar Urals and Spitzbergen has been carried out since 1970 (Suhanov, *et. al.*, 1974; Zagorodnov and Zotikov, 1981). Several tens of bore holes have been drilled to an accumulated length of 7 km. This includes more than 1 km of cored hole. Generally, holes were drilled to bedrock, the maximum depths being 368 m for cored holes and 586 m for uncored holes.

The Hydro-Thermal Drill

For the rapid drilling of shallow (20 m) holes in clean or contaminated ice, a mobile hydro-thermal drill was constructed (Fig. 3). The holes may be needed for installing ablation cables, or for measuring the thickness of ice mounds.

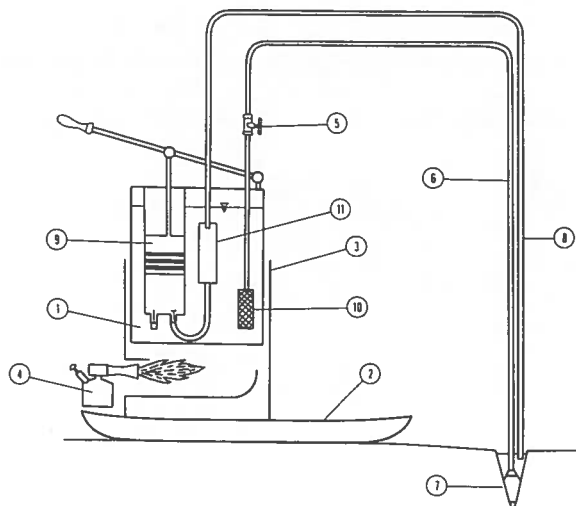


Figure 3. Hydro-thermal drill unit.
 (1) Water tank. (2) Sled resting on ice or snow surface. (3) Weather protection housing. (4) Gasoline blow torch. (5) Control valve. (6) Pipe leading to the drill head. (7) Drill tip, 1.5-2 mm diameter. (8) Water return pipe. (9) Piston pump for providing water pressure. (10) Inlet water filter. (11) Pump filter.

The drill has been successfully tested on the Pamir Glaciers and on various ice mounds in Eastern Siberia.

It consists of a tank mounted on a sled and protected by a heat insulating housing, inside of which is mounted a blow-torch that burns gasoline. Water is heated in the tank and pumped via a flexible hose to the drill tip. On the return stroke of the pump, water in the hole is transferred back to the tank for reheating. The use of the two filters shown in Fig. 3 is very important to prevent the clogging of the drill and the pump while drilling in contaminated ice.

The weight of the unit is 30 kg. The drilling rate is about 1 m/min at a water flow rate of from 7 to 10 m/s.

FUTURE DEVELOPMENTS

There are plans for further improvement of the electro-thermal equipment, firstly, to make it possible to drill in contaminated ice without wasting excessive time cleaning the base of the bore hole, and, secondly, to recover an oriented core and a core not saturated with water from the melting of the firn.

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EQUIPMENT AND TECHNOLOGY FOR CORE DRILLING IN MODERATELY COLD ICE

V.V. Bogorodsky and The Arctic and Antarctic Research Institute,
V.A. Morev Leningrad, U.S.S.R.

ABSTRACT

The equipment for thermal coring in ice as cold as approximately -30°C is described. Ethyl alcohol is used as the hole filler and its use together with glycerol is discussed.

INTRODUCTION

Glaciers in which the temperature is not lower than about -33°C are considered to be moderately cold. All polar glaciers, with the exception of the interior parts of the Antarctic Ice Sheet, fall into this category.

The depth of dry holes drilled in glaciers is restricted by the plastic properties of ice, which cause hole contraction. For successful drilling in such glaciers, it is necessary to fill the holes with fluid to compensate for the hydrostatic ice pressure. A solution of ethyl alcohol mixed with water was found to be a suitable filler. This solution permitted the use of light weight drilling equipment and improved the quality of the core.

DRILLING EQUIPMENT

The ETB-3 electro-thermal core drill was developed for drilling in moderately cold ice. It is shown schematically in Figure 1. It consists of the annular heater shoe fixed at the lower end of the two concentric barrels which are fitted with three core grippers. A piston slides inside the inner (core) barrel, which is initially filled with the anti-freeze solution by means of an inlet nozzle. At the upper end of the

drill is a spring loaded cable termination. The drill is suspended in the hole by means of a single conductor armored electro-mechanical cable. Power is transmitted through the central conductor and the armor (Morev, 1972; 1974).

The drill operates in the following way. The piston is set in its lowest position and the core barrel is filled with an ethyl alcohol-water solution of required concentration before the drill is lowered into the hole.

When the drill shoe is in contact with the bottom of the hole, the power is applied to the heaters causing the shoe to melt an annular space in the ice. The core passes into the core barrel and moves the piston upwards. As a result, the solution is expelled from the inner barrel through holes in the upper end. It percolates down the space between the concentric barrels to the base of the hole where it mixes with the new melt water.

When the core barrel is filled with core, the winch is suddenly reversed, and the jerk causes the core grippers to become engaged with the core which then breaks across. After raising the drill to the surface the operators put the drill on a tilting table where the core is removed and the barrel refilled with new anti-freeze solution. The drill is then ready to be lowered back down the hole.

The auxiliary equipment includes a winch with electric motor drive, a plumb bob and dynamometer (for measuring cable tension) and a counter for

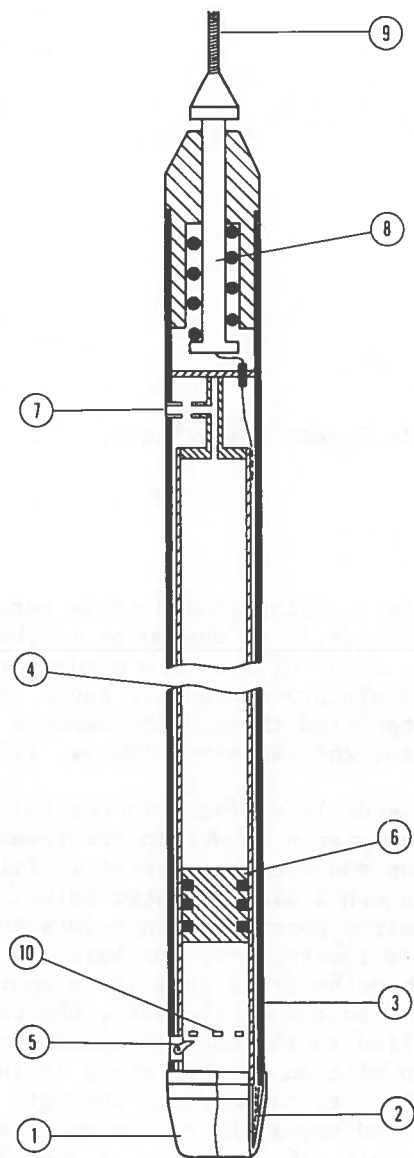


Figure 1. Schematic diagram of the ETB-3 electro-thermal core drill. (1) Heater shoe. (2) Nichrome heater wire winding. (3) Outer barrel. (4) Inner core barrel. (5) Core grippers. (6) Sliding piston. (7) Inlet for injecting anti-freeze into the core barrel. (8) Spring loaded cable termination assembly. (9) Electro-mechanical cable.

measuring the length of the cable in the hole.

The overall drill length is only 0.7 m longer than the core barrel. The use of small sized (8.6 mm diameter) cable meant a reduction in the size, weight and power rating of the hoist. Further, the utilization of the melt water for back filling the holes reduces

the amount of special filler needed.

At present, we believe that this drilling equipment is the lightest and the most effective. The cores and the holes can be used for most common studies.

The drill specifications are:

Heater shoe outer diameter,	108 mm
Heater shoe inner diameter,	84 mm
Hole diameter,	112-120 mm
Core diameter,	78-80 mm
Core length,	1-7 m
Drill weight,	25-180 kg
Power consumption,	1-4 kW
Drilling rate,	2-6 m/h.

The concentration of the solution used for drilling depends on the ice temperature, and may be determined from the nomograph shown in Figure 2. This nomograph shows that when filling the drill with 96 % ethyl alcohol, the coldest ice that may be safely drilled, has a temperature of -33°C . This condition restricts the use of the ETB-3 drill.

In glaciers with a positive temperature gradient (temperature increasing with depth) the concentration of the alcohol solution decreases with depth. The resulting density structure prevents liquid convection and ensures a long term life of the hole.

Observations at the Vavilov Dome (Severnaya Zemlya) were conducted at several bore holes for 2-3 years. A small quantity of ice crystals was always present in eutectic solution. The ice slush crystals were suspended in solution and partly sticking to the wall of the hole. It was observed that, provided the temperature gradient was positive, the crystals do not float up or form shuga (slush) plugs.

With an inverted temperature distribution convection of the liquid and the subsequent formation of shuga plugs is possible.

Convective fluid movement starts when the reversed temperature gradient, dT/dz reaches a critical value given by (Ostroumov, 1952; Krige, 1939):

$$dT/dz = C^4 \nu \kappa / g \beta R^4 \quad (1)$$

where T is temperature,
 z is depth,
 C is a characteristic parameter,
 ν is the kinematic viscosity of the fluid,
 κ is the thermal diffusivity of

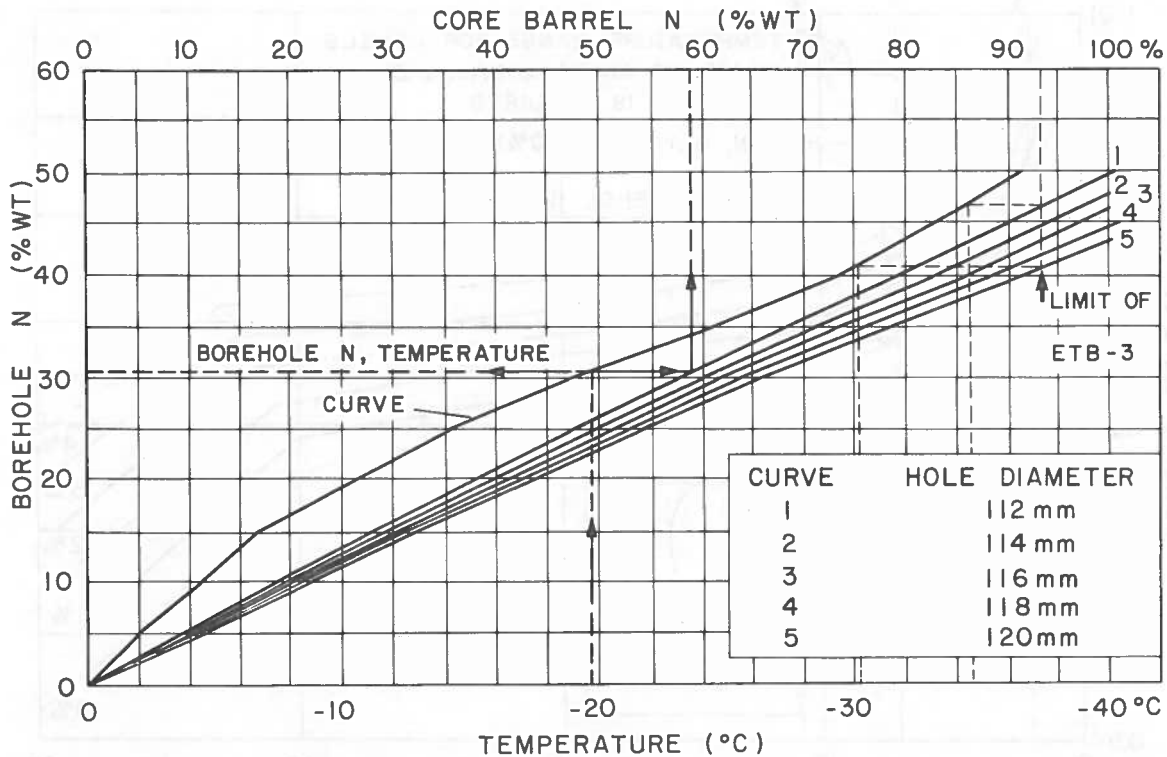


Figure 2. Nomograph for the estimation of solution concentration of ethyl alcohol to be mixed with melt water.

the hole fluid,
 g is the acceleration due to gravity,
 β is the coefficient of volume expansion of the fluid and
 R is the bore hole radius.

The coefficient β is determined from the difference of eutectic solution densities as a function of temperature. The diffusivity of the solution is determined by the method described by Ostroumov (1952) using the relationship between the heat capacity of the ice and the solution at the eutectic point.

Using equation (1) values of the critical gradient have been computed for different temperatures. The results, which yield conservative estimates, are shown in Figure 3.

There were no problems encountered with drilling using the alcohol-water solution even with reversed temperature gradients 30-50 times the critical one. However, in these cases, some slush formation was observed some time after the drilling was completed. At Lomonosov Plateau (Spitzbergen) where the reversed temperature gradient is 6000 times greater than the critical one problems were encountered during the drilling.

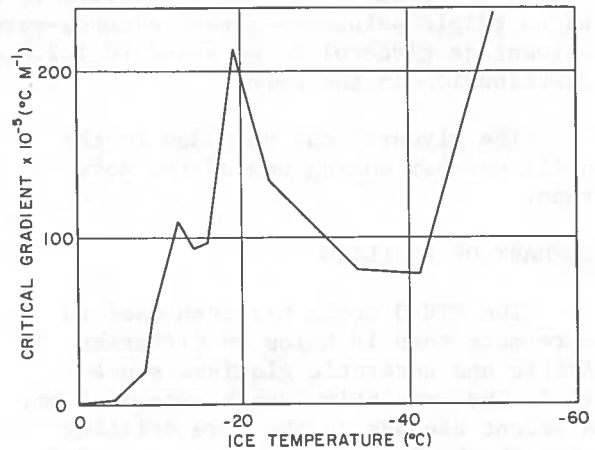


Figure 3. Plot of critical gradient versus temperature of the solution.

For long term bore hole life, where a reversed temperature gradient exists, a loading fluid, such as glycerol, should be added. The quantity of glycerol that should be added depends on the temperature distribution in the hole and may be estimated from the nomograph given in Figure 4. The maximum quantity of the glycerol should be released at the point of minimum ice temperature.

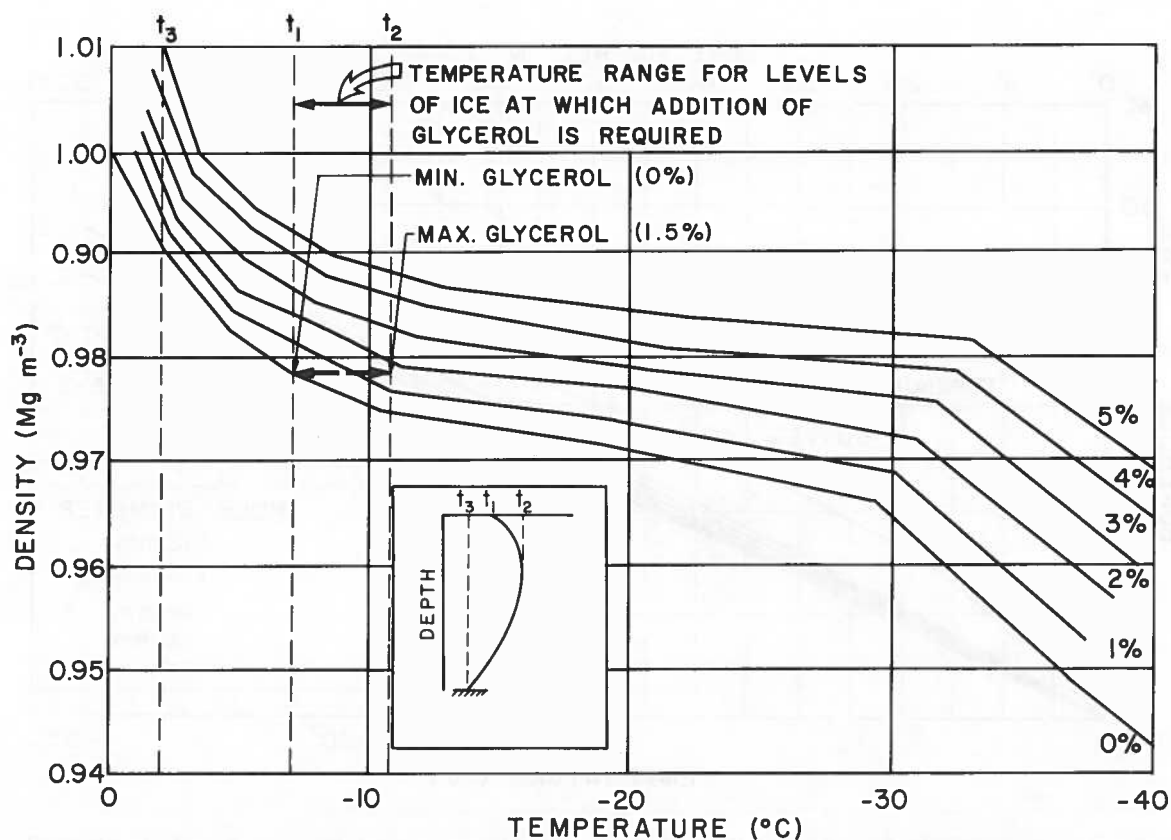


Figure 4. Nomogram for the estimation of the required amount of glycerol to be added to triple solutions (ethyl alcohol-water-glycerol). Each curve corresponds to a percentage glycerol to be added (0,1,2,3,4,5 %) according to the temperature distribution in the hole.

The glycerol can be added to the drill chamber during one of the core runs.

SUMMARY OF DRILLING

The ETB-3 drill has been used to core more than 10 holes in different Arctic and Antarctic glaciers since 1972. The cumulative depth exceeds 5 km. A recent use was in the core drilling through the Ross Ice Shelf at site J-9 (Zotikov, 1979).

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LIQUID FILLERS FOR BORE HOLES IN GLACIERS

V.A. Morev and The Arctic and Antarctic Institute,
V.A. Yakovlev Leningrad, U.S.S.R.

ABSTRACT

An evaluation is made of the different types of liquid fillers that could be used in bore holes in glaciers.

INTRODUCTION

Liquid bore hole fillers are used to compensate for the hydrostatic pressure exerted by the ice during and after drilling. Fillers may be either hydrophobic or hydrophylic.

PROPERTIES OF FILLERS

Liquid fillers should meet the following requirements:

- (1) Their freezing temperature should not be warmer than the glacier temperature.
- (2) Their density should be equal to or greater than the density of glacier ice but it should be less than the density of water.
- (3) The viscosity of the filler should not interfere with the motions of the drill.
- (4) The fillers should be non-toxic and they should not lead to contamination of the environment or the ice core.
- (5) Their electrical conductivity should be low.
- (6) They should be easy to handle and safe to work with under all conditions.
- (7) They should be easily available and inexpensive.

The hydrophobic fillers, which are

petroleum based, should be loaded. The known loading liquids such as trichloroethylene and tetrachloromethane are toxic and strong solvents. If used, they should be handled with special care. The safety measures required are not always feasible in the field.

The hydrophylic, or water based solutions, are found to be most suitable for filling bore holes. A number of different salts were studied (NaCl , CaCl_2 and MgCl_2) as well as liquid hydrocarbons (alcohols, glycerol and ethylene glycol). It was found that methyl alcohol is the most appropriate filler, but its toxicant properties preclude its safe use. As an alternative, ethyl alcohol was chosen as the filler. The density of its eutectic solutions lie between the densities of ice and water. Its viscosity is sufficiently low that winching operations are not adversely affected by the presence of the hole fluid. The use of this fluid does not lead to contamination of the environment, nor does it appear to compromise any of the bore hole or core studies. Thermal drills used in conjunction with an alcohol-water solution are easy to operate, light weight and reliable. The efficient use of the melt water to back fill the hole obviously lessens the amount of filler solution required to be transported to the drill site.

It is known by measurement that the filler poured into the bore hole will achieve the temperature of the surrounding ice in 7-10 days. In those glaciers

where the temperature gradient is positive, the solution density increases with depth. This precludes convection in the solution and promotes a longer bore hole life.

If the temperature gradient in the ice (and hence the bore hole) is anywhere negative, then this section of the fluid column is liable to undergo convection. This may be accompanied by shuga (slush) formation. In order to stabilize this section of the bore hole by maintaining a constant density or by increasing it slightly, glycerol should be added.

The properties of the solution to be used are determined in the following way. The freezing temperature is determined both from reference data and from laboratory tests. The densities of the eutectic solutions may be calculated from Mendelejev's (1934) formula:

$$\rho_t = \rho_{20} + D(20-t) - E(20-t)^2 \quad (1)$$

where D and E are empirical coefficients, t is the solution freezing temperature and ρ_{20} is the solution density at 20°C.

The solution density values obtained from equation (1) were determined experimentally to third place accuracy.

The freezing temperatures and densities of triple solutions were also obtained experimentally.

Figure 1 shows the dependence of the freezing temperature of the ethyl alcohol-

hol-water solution on its concentration.

Figure 2 shows the dependence of the density of the ethyl alcohol-water eutectic solutions on the solution temperature.

Figure 3 shows the dependence of double and triple solution viscosity on temperature.

APPLICATIONS

In temperate glaciers, the pure melt water becomes the filler. However, the upper layers of the glacier may lose heat and freezing of the upper borehole water may take place. If it is necessary to preserve the hole, the upper 10-20 m should be cased and this part of the hole should be filled with an anti-freeze liquid.

In cold glaciers with a positive temperature gradient, the water-alcohol solutions prolong the holes life. In glaciers with a complex temperature distribution, triple loaded solutions are recommended, to ensure that they have constant or increasing density with depth.

Alcohol-water fillers have particular applicability when thermal drills are being used.

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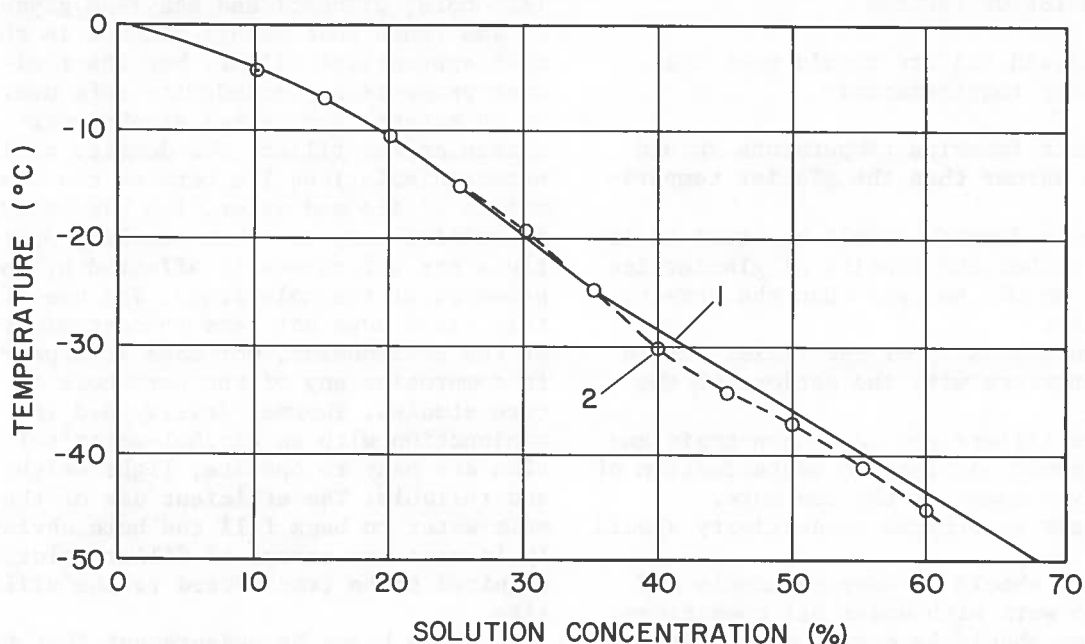


Figure 1. The dependence of the freezing temperature of ethyl alcohol-water solution on the solution concentration by weight. Curve 1 is calculated. Curve 2 is experimental.

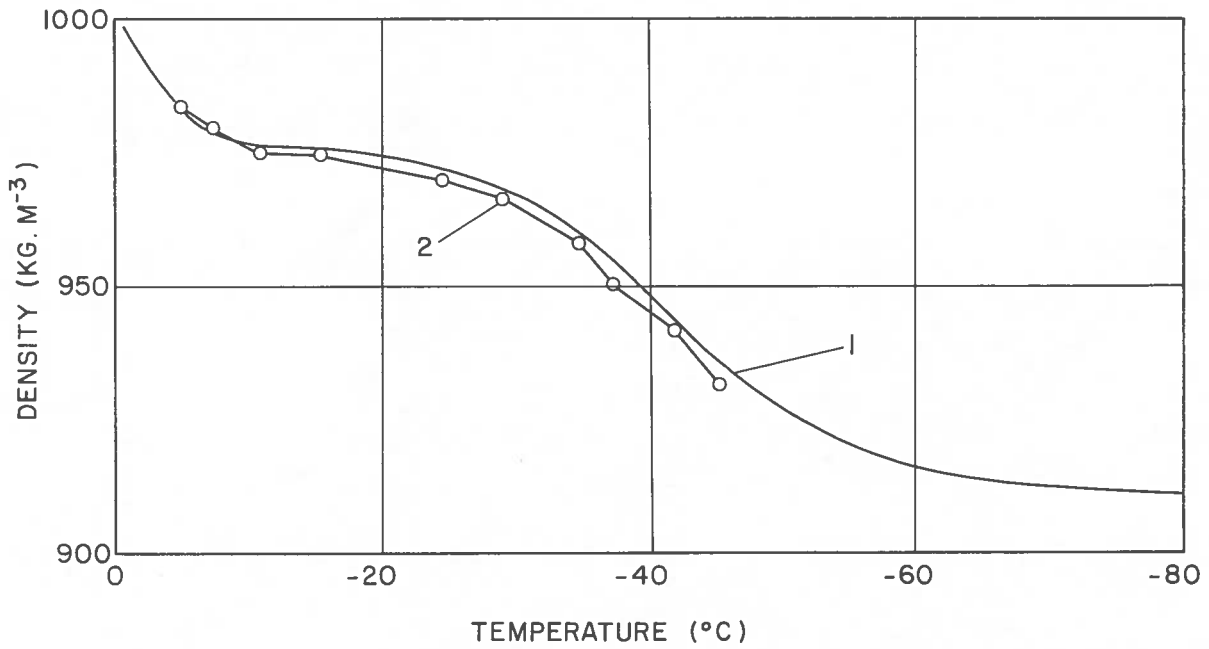


Figure 2. The dependence between the density of the ethyl alcohol-water solution and its freezing temperature. Curve 1 is calculated. Curve 2 is experimental.

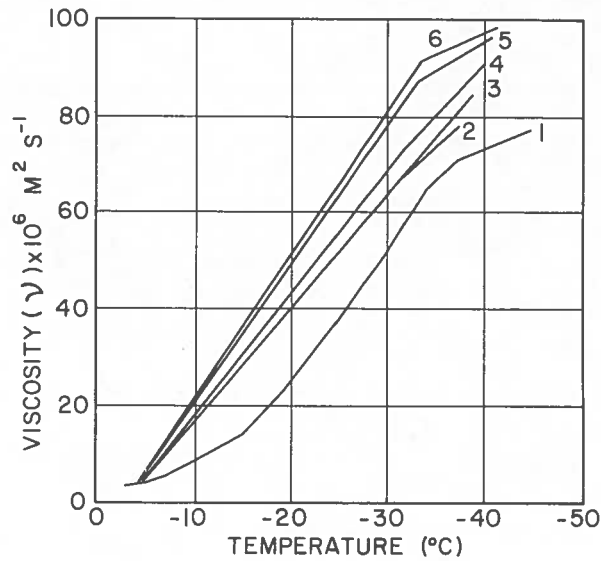


Figure 3. Dependence between the viscosity of an ethyl alcohol-water-glycol solution and its freezing temperature. Curves 1 through 6 correspond to 0 % through to 5 % glycol by weight.

SELECTION OF A LOW TEMPERATURE FILLER
FOR DEEP HOLES IN THE ANTARCTIC ICE SHEET

B.B. Kudryashov
V.K. Chistyakov and
V.M. Pashkevich

The Leningrad Mining Institute,
Leningrad, U.S.S.R.

and
V.N. Petrov

The Arctic and Antarctic Research Institute,
Leningrad, U.S.S.R.

ABSTRACT

The development of a suitable low temperature liquid filler for the 2000 m deep hole at Vostok station, Antarctica, is described.

INTRODUCTION

In deep drilling through the East Antarctic Ice Sheet it is essential to maintain stability of the hole wall under increasing hydrostatic pressure and pressure. The amount of hole closure expected is primarily determined by the ice rheology and temperature as well as the duration and type of drilling.

The filler should meet certain requirements:

- (1) The freezing temperature should not be higher than -60°C .
- (2) It should not deteriorate when in contact with ice.
- (3) It should be water immiscible.
- (4) It should have low viscosity at low temperatures.
- (5) It should be easy to handle, safe to work with, easily available and inexpensive.

Experimental studies of a number of hydrophyllic (alcohol-salt solutions) and hydrophobic liquids (immiscible with water) indicated the limited use of the former since they tend to interact with the ice if great care is not taken. Hydrophyllic liquids can be used conveniently when thermal drilling at tempera-

tures down to about -30°C .

For deep drilling in the East Antarctic Ice Sheet at temperatures near -60°C a special low temperature filler, developed at the Leningrad Mining Institute, was used.

FILLER PROPERTIES

The filler is hydrocarbon based and its density may be varied from 0.880 Mg m^{-3} to 0.920 Mg m^{-3} by the addition of a loading material. Due to its low viscosity and high immiscibility with water, the filler kept the lower bore hole free of slush. The 2000 m deep hole at Vostok station was drilled in 1981-82 with the use of the LMI filler. No significant hole contractions were recorded.

USE OF THE FILLER

The filler level in the hole should not be less than about 100 m from the top of the hole, since the filler will permeate the firn. To be very economical this level may be set even lower, provided hole closure is not significant.

To calculate the filler density required to take account of the changing ice properties with depth and temperature, an analytical expression was developed. It is derived from an equation for the wall strain rate.

The final operational equation (Salamatin, *et al.*, 1981) is:

$$\rho_s = \rho_i - 10^2 n (gH)^{-1} (At)^{-1/n} \times (\ln R_0/R)^{1/n} \quad (1)$$

where ρ_s and ρ_i are the densities of the drilling solution and the ice (Mg m^{-3}),

H is the depth of the hole (m),

R_0 and R are the initial and current hole radii (mm),

n is the dimensionless power index in the flow law,

A is the parameter in the flow law which is dependent on the physical properties of the ice ($\text{MPa}^{-n} \text{s}^{-i}$) and

t is the time elapsed (s).

Calculations made using this expression (1) for the Vostok station conditions are in good agreement with the field drilling results in the No. 3G hole in 1980 (Fig. 1).

Referring to Figure 1, the drilling down to 1415 m was made with incomplete balance of the ice pressure. The upper level of the filler (density 0.810 Mg m^{-3}) was maintained at from 200 to 450 m below the surface. The hole diameter was measured periodically. Also, the drilling rates were watched carefully. These observations indicated that wall contraction did not exceed 0.5-1 mm.

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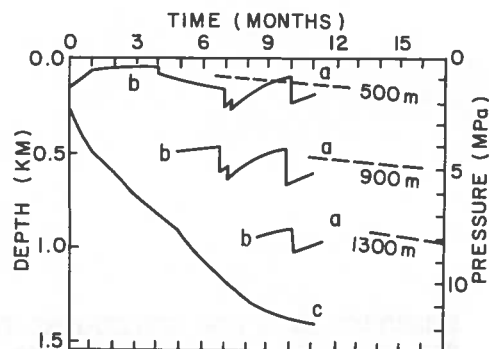


Figure 1. The calculated and observed liquid pressure in the No. 3G bore hole during the 1980 Vostok station operations. Curves (a)- the calculated and required pressures for depths of 500 m, 900 m and 1300 m. Curves (b)- the observed pressure values for depths of 500 m, 900 m and 1300 m. Curve (c) is the drilling progress plot.

NEW EQUIPMENT AND
TECHNOLOGY FOR DEEP
CORE DRILLING IN COLD GLACIERS

V.V. Bogorodsky, V.A. Morev,
V.A. Pukhov and V.M. Yakovlev

The Arctic and Antarctic Research
Institute, Leningrad, U.S.S.R.

ABSTRACT

A new electro-thermal drill, ETB-5 was developed from the model ETB-3, for the purpose of coring in glaciers which contain ice colder than -33°C . The unit and its functioning principles is described.

INTRODUCTION

The powerful and reliable electro-thermal drill, ETB-3 (Morev *et. al.*, 1981) is used for drilling in ice when the temperature is not lower than -33°C . The upper layers of the central east Antarctic ice sheet have temperatures as cold as -57°C . The attempted deployment of ETB-3 under these conditions would require a considerable increase in core barrel diameter, and, accordingly, excessive quantities of electrical power and liquid fillers. Instead, for optimum dimensions of core and hole, using reasonable power levels, the ETB-5 drill was developed.

THE DRILL UNIT

Figure 1 is a schematic diagram of the ETB-5 drill unit. It consists of a drill heater shoe attached to two concentric barrels, the inner one of which serves as the core barrel. Above the shoe, are the three core grippers. A lower piston moves within the confines of the core barrel. Above, there is another set of concentric barrels, the inner one of which contains the upper piston which is connected to the first by a connecting rod. There are two sets of

fluid filling nozzles, one set for each chamber and a set of inlet ball valves.

At the top end there is an end cap assembly and a spring loaded cable termination.

The drill is suspended in the hole by a single cored armored cable (KG-1-40-180) with a diameter of 8.6 mm. Power applied to the drill heaters, varies from 3 to 4 kW. Energy losses in a 4 km long cable amount to 3 to 4 kW. The maximum power consumption would therefore be up to 8 kW (supplied at 600 to 800 V).

The core barrel may be made 1.5 m to 3 m long, as is the case with the ETB-3 drill to which it is analogous in principle.

WORKING PRINCIPLE OF THE DRILL

The first step is to fill the upper tank and the core barrel with anti-freeze solution of the required concentration, the pistons being set at their lowest position. After lowering the drill to the base of the hole and switching on the power, the melting process at the annular drill face commences. During this process, the core lifts the pistons, as a result of which, the solution is expelled from the core barrel and travels down the space between the concentric barrels to the lower drill hole area, where, after mixing with the melt water, it produces the first solution. (If the core barrel is filled with 96 % alcohol, then the resulting lower solution has a strength of about 50 % alcohol).

As it is expelled by the rising

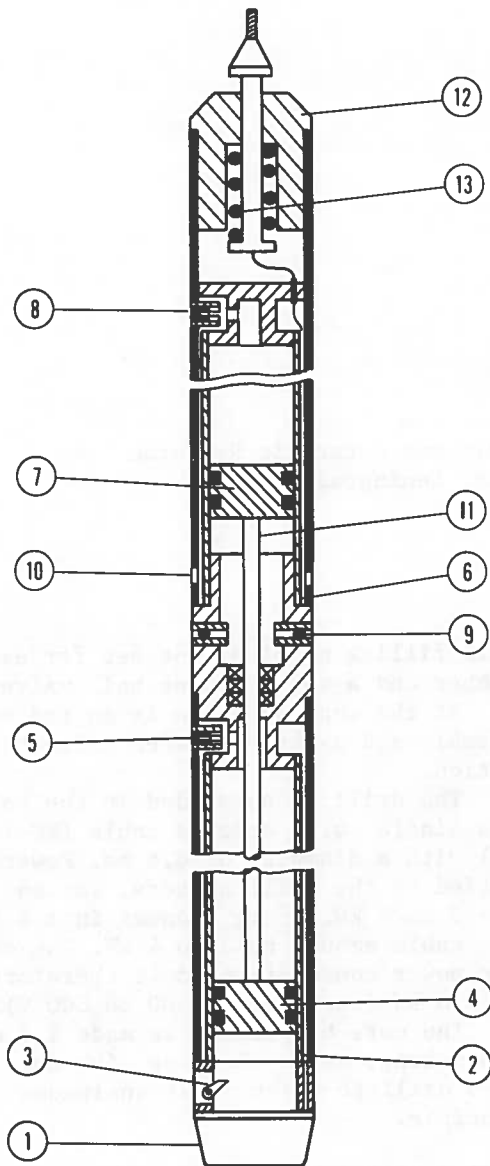


Figure 1. Schematic diagram of the ETB-5 electro-thermal core drill.

(1) Heater shoe. (2) Lower double tubes. (3) Core grippers. (4) Piston with rings. (5) Lower fluid filling inlets. (6) Upper double tubes. (7) Upper piston with rings. (8) Upper fluid filling inlets. (9) Inlet pressure valves. (10) Fluid discharge openings. (11) Connecting rod. (12) End cap assembly. (13) Spring and cable termination assembly.

upper piston, the upper fluid is forced through the space between the barrels and out the openings (10) shown in Fig. 1. By means of the inlet valves (9), the original, lower solution is now extracted from the hole by suction and collected in the lower end of the upper chamber.

In this way, an anti-freeze solution of the required concentration is distributed more evenly along the length of the barrel. As a result, unnecessary excess melting of the bore hole walls and the subsequent dilution of the anti-freeze solution is minimized. Excessive dilution and cooling of the solution could lead to shuga (slush) formation.

FIELD TESTING OF THE UNIT

The drill was tested on a glacier of Severnaya Zemlya. It is now being tested at Komsomolskaya Station in east Antarctica, where the near surface temperature is -53°C . The drill equipment sent to Komsomolskaya includes a heated shelter, mounted on a steel transport sled. The total weight of the equipment including the sled is about 18,000 kg. The shelter contains a 16 kW diesel power unit, a cable winch with a drum capacity of about 5 km of cable and an electric drive with a power of 7 kW. Above these units there is a tower 9 m high. Other items include a control panel, and a dynamometer. Hot water heating is by excess heat from the diesel generator and there is natural and artificial ventilation.

After its extraction from the hole the drill is placed on a table and the core removed. The chambers are then refilled with anti-freeze solution. These procedures are carried out in a special unheated cabin where the core examination and analysis is also performed. The dimensions of the drill shelter are 3.5 m x 8 m and of the unheated cabin 2.5 m x 5 m.

To provide vertical holes, the cable is kept under tension. This is controlled by partially activating the spring in the end cap of the drill. The tension may be measured using the dynamometer or using sensors installed in the spring assembly. Due to the lower weight of cable in fluid, it is possible to control the cable tension entirely using surface equipment down to a depth of at least 2.5 km. Tensometers may be used when the sensitivity of surface instrumentation is inadequate.

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APPENDIX
LIST OF REGISTRANTS

- Benson, C.S.
Geophysical Institute
University of Alaska
Fairbanks, Alaska 99701
U.S.A.
Ph. 907 474 7450
- Cameron, R.L.
U.S. National Science Foundation
Division of Polar Programs
1800 G Street
Washington, D.C. 20550
U.S.A.
Ph. 202 357 7894
- DePaoli, S.
Dome Petroleum
400 5th Avenue S.W.
Calgary, Alberta
Canada
Ph. 403 260 8180
- Donnou, D.
Laboratoire de Glaciologie
C.N.R.S.
BP 53 X
38041 Grenoble CEDEX
France
Ph. (76) 42 58 72
- Dörr, R.
Department of Civil Engineering
Ruhr University
Postfach 102148
4630 Bochum
West Germany
Ph. 02341 700 6135
- Gillet, F.
Laboratoire de Glaciologie
C.N.R.S.
BP 53 X
38041 Grenoble CEDEX
France
Ph. (76) 42 58 72
- Giovinetto, M.B.
Department of Geography
University of Calgary
2500 University Drive N.W.
Calgary, Alberta T2N 1N4
Canada
Ph. 403 284 5586
- Gundestrup, N.S.
Geophysical Isotope Laboratory
University of Copenhagen
Haraldsgade 6
DK 2200
Copenhagen N
Denmark
Ph. 1 83 85 00
- Hansen, B.L.
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588
U.S.A.
Ph. 402 472 2760
- Holdsworth, G.
National Hydrology Research Institute
Environment Canada
101-4616 Valiant Drive N.W.
Calgary, Alberta T3A 0X9
Canada
Ph. 403 288 0550
- Jeffries, M.O.
Department of Geography
University of Calgary
2500 University Drive N.W.
Calgary, Alberta T2N 1N4
Canada
Ph. 403 284 5596
- Kersten, L.
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588
U.S.A.
Ph. 402 472 2760

Koci, B.
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588
U.S.A.
Ph. 402 472 2760

Kohnen, H.
Institut für Geophysik
Westf. Wilhelms Universität
Correns strasse 24
D-44 Münster
West Germany
Ph. 0251 83 3591

Kubo, Y.
CR Engineering Laboratory
4-44-3 Minami-Ogikubo
Suginami-ku
Tokyo
Japan 167
Ph. 03 333 7306

Kuivinen, K.C.
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588
U.S.A.
Ph. 402 472 2760

Litwak, J.
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588
U.S.A.
Ph. 402 472 2760

Marshall, P.S.
Arctic Alaska Testing Laboratory
Box 843 2055 Hill Road
Fairbanks, Alaska 99701
U.S.A.
Ph. 907 452 6181

Mokievsky-Zubok, O.
National Hydrology Research Institute
Environment Canada
Ottawa, Ontario K1A 0E7
Canada
Ph. 613 997 2385

Rand, J.
U.S. Army Cold Regions Research and
Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755
U.S.A.
Ph. 603 643 3200

Schlager, F.M.
Government of Alberta
11th Floor, Pacific Plaza
10909 Jasper Avenue
Edmonton, Alberta T5J 3M8
Canada
Ph. 403 427 4809

Skvarca, P.
Instituto Antártico Argentino
Division Glaciología
Cerrito 1248
1010 Buenos Aires
Argentina
Ph. 1 44 1689

Suzuki, Y.
Institute of Low Temperature Science
Hokkaido University
Sapporo 060
Japan
Ph. 011 711 2111 (5490)

Taylor, P.L.
Glaciology Project Office
Department of the Interior, U.S.G.S.
Suite 850, 1201 Pacific Avenue
Tacoma, Washington 98402
U.S.A.
Ph. 206 362 1074

Verrall, R.I.
Defence Research Establishment Pacific
F.M.O. Victoria
British Columbia VOS 1B0
Canada
Ph. 604 388 1503



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