ICE CORE DRILLING

Editors

C. RADO

D. BEAUDOING

Laboratoire de Glaciologie et Géophysique de l'Environnement

Grenoble - France

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PREFACE

The International Ice Core Forum (ICCF) was founded in Bern by several participants of the Bern meeting (April 1987) on Ice Core Analysis held under the auspices of SCAR.

One of the main conclusions of this group, which convened for the first time in Bremerhaven on 10 September 1987 was that it is time for another drilling workshop, where mainly technicians could meet and discuss new technical developments in the field, since the Calgary symposium of 1982 : a questionnaire regarding this workshop was circulated by K.H. Bassler (AWI, Bremerhaven) at the end of September 1987. The responses demonstrated the timeliness of such an initiative. The LGGE (Grenoble) then proposed to organize a 1 week workshop in October 1988. Its scope, date and venue were decided based on the requirements of those who planed to participate. Fourty people from Europe, USSR, USA, Japan ... attended the meeting held at Grenoble, France from the 10th to the 14th of October, 1988. The list of attending registrants is given in an appendix. 25 papers were presented, but some of them were not included in the proceedings because we did not get the manuscript in time or because of their "too scientific" topic.

Support for the workshop came from the Scientific Committee on Antarctic Research, the Centre National de la Recherche Scientifique, the Université Joseph Fourier of Grenoble and the registrants fee.

Manuscript preparation was the responsability of authors except for non-english contributors : their paper has been corrected. The typing has been made by V.D.I. in Grenoble and the editing by the LGGE of Grenoble.

The local organizing committee

GERMAN INTERMEDIATE ICE CORE DRILLING SINCE 1981

- Technique and Experience -

by

K.-H. Bässler and H. Kohnen
Alfred-Wegener-Institute for Polar and Marine Research.
Bremerhaven, FRG.

1 - ABSTRACT

The development of a Rufli type drill system for electromechanical ice coring, it's use at several locations in the Antarctic and future modifications based on experience during field work are outlined. A short video record, taken during the German Antarctic Expedition in 1987 in the Ritscher Hochland and the Ekström ice shelf gives an impression of the drill procedure and occuring problems.

2 - INTRODUCTION

Since the International Geophysical Year scientific investigations on ice cores and in drill holes are important tools for glaciological research.

Down to depths of 30 m ice cores can be obtained with hand operated drills.

Because of the technological requirements only a few drill systems for greater depths are available. Most of these systems are designed for drillings in dry holes down to 400 m.

Four nations have developed techniques for deeper drilling (to 4000 m) using expensive drill technologies with liquid filled holes. At present most international interests in ice

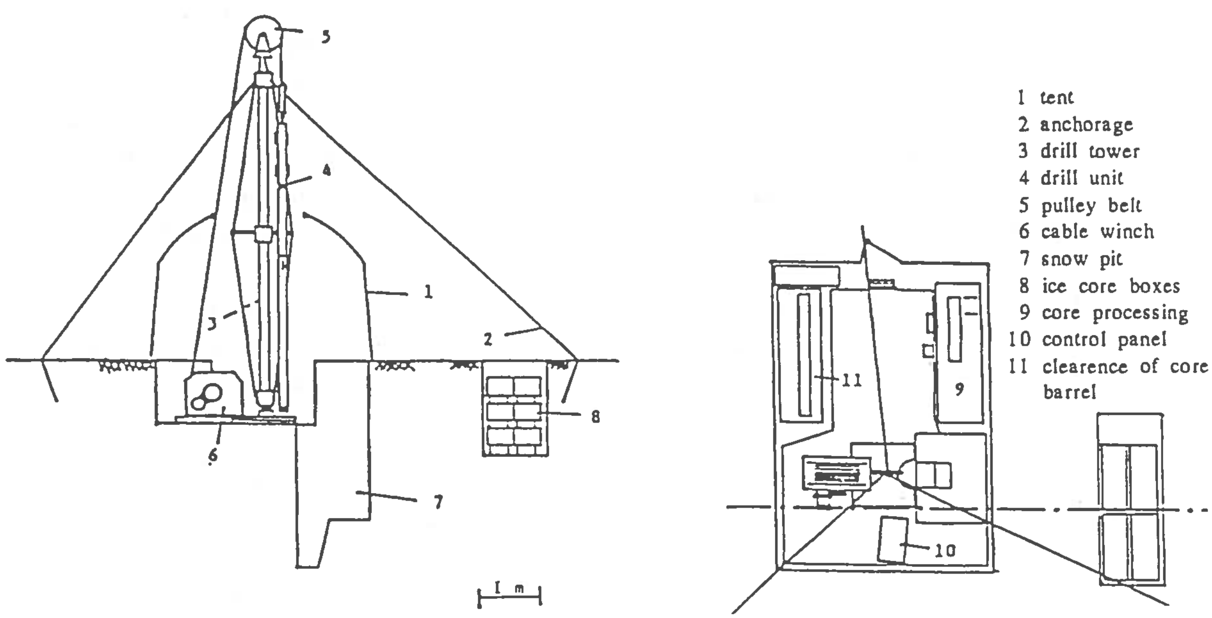

Fig. 1 - Arrangement of the drill equipment

core research can be satisfied with intermediate cores.

3 - REVIEW OF THE DRILL DEVELOPMENT

In 1981 the Institute for Soil Mechanics and Foundation Engineering at the Ruhr University Bochum (RUB) built the first German intermediate ice core system following the design of the Swiss drill with support of H. Rufli and sponsored by the Alfred-Wegener-Institute for Polar and Marine Research (AWI). In period of 6 months the system was available for the first drilling in the cold ice of the Antarctic near the German station "Georg von Neumayer".

A test on an Alpine glacier (Kaprun) gave the possibility to check the main functions. The present arrangement of the drill equipment is shown in fig. 1. Housed in a tent (Hansen Weather Port) the drill system, mainly the same as described in Jessberger et al, 1984, except with a few modifications is operated.

Based on the experience from two drill holes (50 m ; 73 m) some modifications on the cutter heads were performed between the Antarctic seasons 1982 and 1983. A leaf spring antitourque system and a lighter winch with Kevlar cable was introduced to reduce the weight of the system and to improve the penetration rate and the core quality.

In January 1983 the Ekström ice shelf was penetrated (203 m / 15 days) and the drill got stuck at the bottom. In 1983 a new drill unit was built and using rounded cutters (Holdsworth, 1984) the equipment was tested on the Jungfraujoch. Good experience was obtained with the rounded cutters during a drilling on the Filchner/Ronne ice shelf in 1984. A 100 m core of good quality was drilled. The core quality improved from 70 m onwards after replacing the angular SIPRE cutters by the rounded cutters. The greater area of cutting seems to reduce the stress in the core. The comparison of the recorded speed of rotation between the angular and rounded cutters in fig. 2 (Jessberger et al, 1985) exhibits a strongly fluctuating decrease for the angular and a constant decrease for the round cutters.

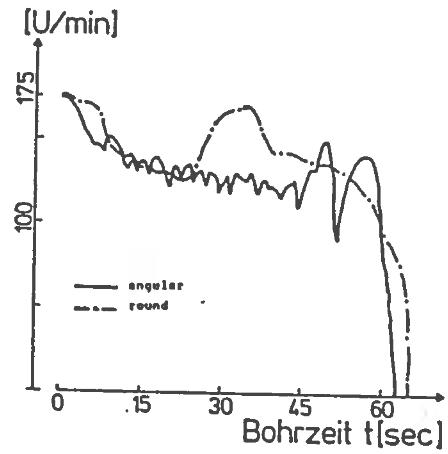

Fig. 2 - Recording of the cutter head rotation.

In 1987 two cores of 42 m and 47 m length were obtained in the Ritscher Hochland 220 km south of "Georg von Neumayer".

Hard thick ice layers of refrozen firn between the accumulated firn hindered further penetration with the rounded cutters. The pitch on the cutter head might have been too great and therefore the fine powder produced in this ice layer instead of coarse chips could not be carried away and the cutters slid. By using the SIPRE cutters a broken core was gained and thereafter further penetration was possible with the rounded cutters. But because of bad core dog design and incorrect epoxy potting of the Kevlar cable the cable failed and one drill unit was lost. With the second unit a hole (204 m) on the Ekstroem ice shelf 70 km south of "Georg von Neumayer" was drilled.

4 - PRESENT AND FUTURE MODIFICATION

The pitch of the cutter head spitals is altered from 60 to 30 deg. New core dogs following the design of Koci, 1987 were manufactured. The conical form of the cutter head (see fig. 3), used earlier for core catching, will be used only near the surface in low density firn in order to prevent damage of the core.

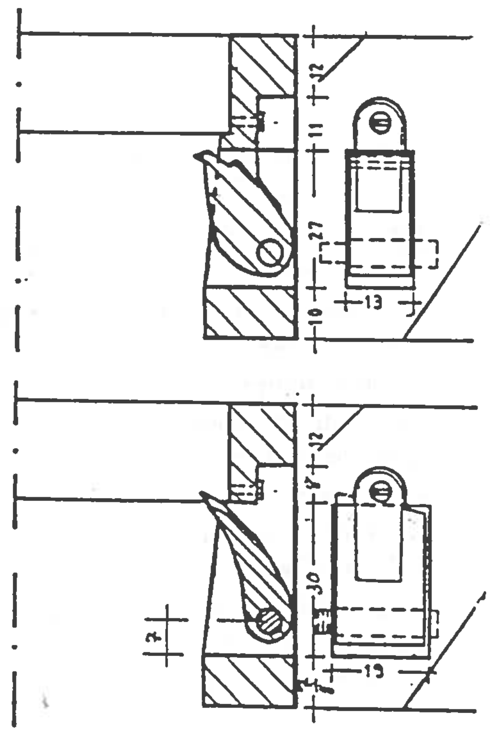

Fig. 3 - Comparison between new and old core dog design.

The cable terminal will be changed. The use of a new commercially available slip ring assembley and a nylon braided Kevlar cable enables splicing in spite of epoxy potting.

An improvment for the winding of the cable will be tried with a new stiffer base plate, a grooved LeBus drum and a LeBus level wind system.

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REFINEMENTS OF THE UCPH SHALLOW DRILL

by

Gundestrup N.S., S.B. Hansen and S.J. Johnsen
Geophysical Institute, Haraldsgade 6
DK-2200 Copenhagen N, Denmark

ABSTRACT

In the period 1975 to 1978, UCPH developed their version of the Rand/Rufli shallow drill. The primary objectives of the drill were : ease of handling, light weight and fast site preparation. In order to realize the primary goals, core length is restricted to 90 cm in solid ice.

Based on experience gained from the UCPH deep drill (ISTUK), the shallow drill was modified to enhance the primary goals, that remained unchanged. The modifications included new cutters, introduction of a pitch controlling shoe, introduction of core catchers and improvements to the slip ring assembly in the winch. The modifications have reduced the drill power to 160 W at 70 m depth and 300 W at 300 m depth. The low power used by the drill has enabled it to recover cores at depths exceeding 300 m. Following the same basic layout, a hand auger has been developed.

INTRODUCTION

Based upon original designs from the SIPRE hand auger, the Icelandic drill (Arnason and others, 1974), the Swiss shallow drill (Rufli and others, 1976) and the US, CRREL shallow drill (Rand, 1976), the first version of the danish shallow drill was developed in the time period 1976 to 78 (Johnsen and others, 1980). The drill uses a leaf spring antitorque system, and as something new, a tiltable tower, just 2.3 m high. Using a tiltable tower, the usual pit used while separating the inner core barrel and the core from the rest of the drill has been replaced with a small incline trench 1.2 m deep, 30 cm wide and 1 m long. In operation, the drill is often used mounted on a "Nansen sledge". This cuts the setup time down to a minimum, and allows several 25 m cores to be retrieved in one day.

The development of the deep drill (ISTUK) led to a better understanding of the cutting process and the handling procedures. Several of the techniques from the deep drill is of general nature, and has been introduced in the shallow drill.

DESCRIPTION

The slip rings in the winch has been improved. Originally, the connections were made with commutator graphite. Dust from the graphite at times created leakage between the rings. Pure metal connections would create a risk of introducing wear on the rings, so the problem was solved with contacts made of 90 % silver and 10 % graphite.

The **cable** is the same steel armored 5.6 mm as purchased in 1976. Although the cable now shows some sign of age, we expect to use the old cable for yet another 12 years. The cable is light weight (12.3 kg/100 m), and the steel cables low elasticity is a prerequisite for operating the hammer in the drill.

The **antitorque section** is also unchanged from the description in Johnsen and others (1980). The antitorque is produced by three 2 mm thick, 20 mm wide and 500 mm long leaf springs. As the torque required is low, the antitorque system never fails, even while drilling in ice with ice layers or loose snow. The flexibility of the springs adjusts to the properties of the snow. The design of the springs is described by Reeh (1984).

The **motor** is the same double Mavilor disc motor. The low power needed after improving the drill head means, that we are using the same double motor for now 12 years. The motor rating is 5 amps nominal, and the maximum current experienced is 3.5 A at a depth exceeding 300 m. The gear is also not changed. The 80:1 reduction "Harmonic Drive" has just been replaced once, while the motor section was used for something else. The motor shaft and the bearing that transmits the cable force to the inner core barrel have been redesigned. The new design is simpler, making use of a more advanced bearing. Drawings are available on request.

The **inner** and **outer core barrel** are also unchanged. The stainless barrels are light and clean, and we see no reason to change. The surface of the inner core barrel is polished. The chips transport between the barrels is maintained by fine grooves on the inner side of the outer barrel. This system works without problem as long as the chips are reasonable coarse, and we have seen no reason to change to the more familiar strips fixed to the outer core barrel. The **auger flights** on the inner core barrel has been replaced with Polyethylene High Density (PEHD) flights, screwed to the inner core barrel. The material has been chosen after advice from B. Koci and H. Rufli, and it has served well for now 5 years in ice temperatures to -32°C. The flights are cut as a spiral from a PEHD tube, boiled in water for an hour, and then quickly clamped in place. Treated this way, the PEHD keeps the new shape. After the spiral is screwed to the barrel, it is turned in a lathe to a diameter that makes the barrel turn in the outer barrel with minimum friction and clearance.

The **electronics** are still the 12 year old SCR control. The main draw back of this control is, that it is relatively open, making snow penetrate the enclosure while drilling : For drilling up to 100 m, the operation normally uses no tent. All equipment is placed directly on the surface without cover. Snow in the control has led to some breakdowns, but as it is easy and cheap to change the SCR regulators, we have not yet build another regulator.

DRILL HEAD

The key changes are made to the drill head. The ISTUK experience showed, that the drill head is probable <u>the</u> most critical item in the drill. Although this drill was operating in a liquid at great depths, we considered the following experience as general :

1 - Use very sharp cutters.

2 - Create a relief angle after **all** cutting edges - also the side of the cutter.

3 - Use aggressive cutters - they produce coarse cuttings that are easily transported by the flight augers.

4 - Make sure, that the drill head is very stable.

5 - Use a rake angle of 45° and a relief angle of 12°.

6 - Control the pitch with a shoe as used in a plane.

7 - Use the a slightly smaller rake angle for the core catchers.

8 - Use a double spring system on the core dogs, keeping them in upright position while not engaged.

9 - Place the core dogs as far down as possible.

10 - Have close tolerance between bottom of drill head and core preventing chips to wedge in between drill head and core.

11 - Keep open space around the core dogs allowing chips the maximum volume.

12 - Clean the drill with a brush and pressurized air. Do not use any solvent.

Figure 1 shows the modified drill head based on these rules. The head is seen from above with part of the head around the core dog cut away in order to expose the core catcher. The core dog turns around a steel pin, and a small screw prevent the pin from falling out. The core dog is pushed against the core by a V-shaped steel wire spring. The head is made of ordinary stainless steel. The surface is polished to enhance chip flow and to minimize the risk of the ice chips to stick to the head. The head is replaceable. It is fixed with 3 screws near the upper rim of the head.

A key point is that the cutters do not determine the penetration rate : The cutters are so aggressive, that they tend to dig themselves down in the ice. This means, that no cutter load is needed, and while drilling the operator controls the winch to keep the cutter load to a minimum. Using very little load on the cutters, and keeping the major part of the weight of the drill in the cable, the drill hole can be nearly vertical. In the deep drill, deeper down in the ice, the cutter load used was negative : we pulled upward the drill after the bits engaged. In the shallow drill, using negative cutter load has not been possible. The reason is probably, that the ice at the bits fractures. In the liquid filled hole, the pressure release is separated from the cutting process. This produces better core quality and a cutting process that dig the bit down in the ice with great force.

The penetration rate (pitch) is determined by shoes mounted on the bits 1 cm after the cutting edge. In Figure 2, that shows the drill head as seen from below, the shoes are clearly visible. Their width are somewhat smaller than the bits, making sure that the side of the shoe gives minimal friction. Note the small hole in the head below the center of the core catchers. One end of the small spring, that keep the core dog in upright position while not engaged, goes down in this hole.

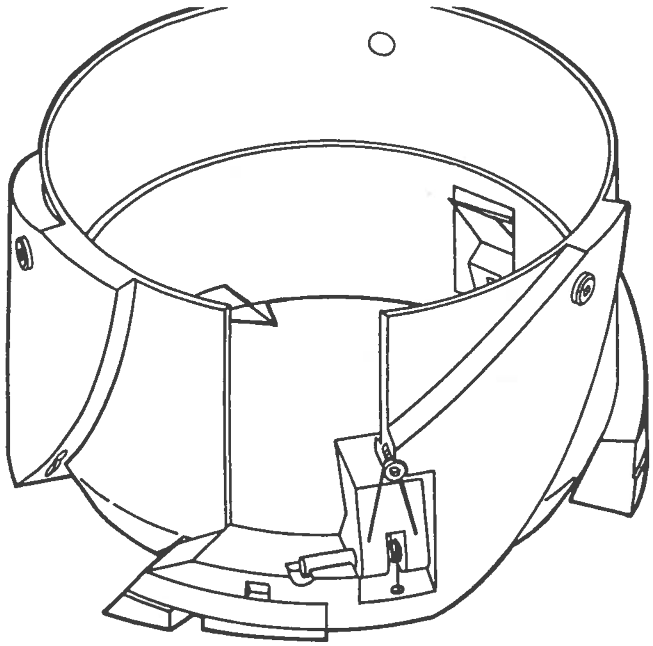

Figure 1 - Drill head used in shallow drill and hand auger as seen from above. Part of the head is cut away to expose the core catcher and its spring. The head is screwed to the inner core barrel with 3 screws. The material is stainless steel for the head, and tool steel for the bits.

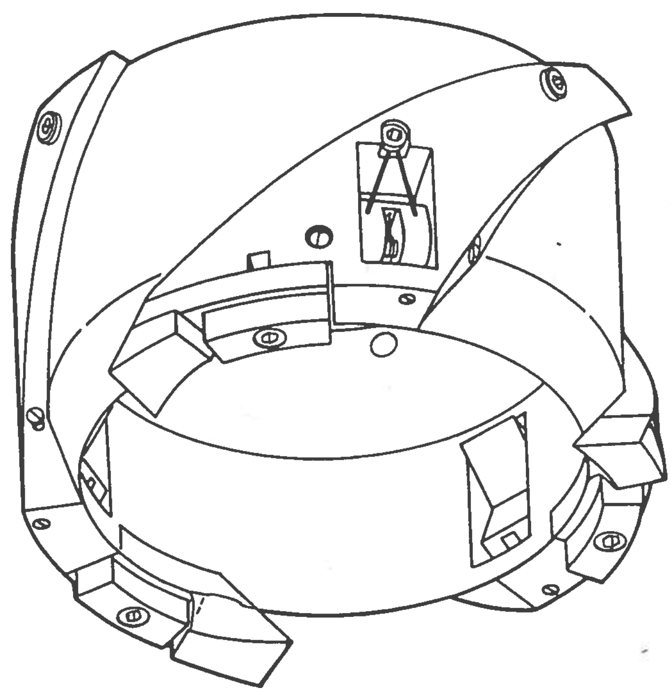

Figure 2 - Drill head as seen from below. On the inner surface, one corecatcher penetrates into the space for the ice core. Note, that the core catcher when not engaged do not fall down - a small soft spring between the core dog and the drill head prevents the dog to fall down. Also seen is the shoes mounted on the bits, after the cutting edge. The size of the shoe allow the handauger to start from the surface even in loose snow. The bits can be removed pushing a tool into a grove in the head.

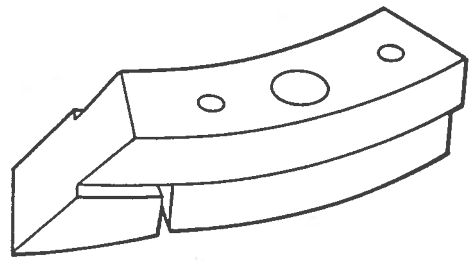

Figure 3 - Bits seen from above. The rake angle (the angle between vertical and the front plane of the cutter is 45°, the clearance angle is 12°. The bits are positioned with two pins, and held in place with a single screw.

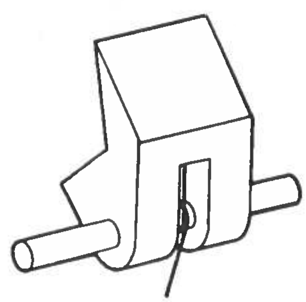

Figure 4 - Core catcher. The core catcher are pushed against the ice core with a small strong V-shaped wire spring. The catcher is prevented from falling into the head when not engaged using a soft spring placed in a grove in the catcher.

The bits, that are replaceable, are shown in figure 3. The bits are made of ordinary tool steel. The rake angle is 45 deg, the relief angle 12 deg leaving a 33 deg wedge of steel. The cutting angles are sharpened very carefully, trying to keep the edges sharp as a "swiss army knife". Also the sides of the cutters are sharpened with a relief angle behind the front edge. As the cutting process in a shallow drill is not quite as critical as in the deep drill, the relief angle at the side of the cutter do not start at the front face, but 0.5 mm behind. Thus, the cutters can be sharpened without changing hole diameter. This works very efficiently - we have used the same set of cutters for many years. The cutters are fastened to the drill head with a single screw, and kept in place with two pins. The shoes are mounted on the cutters.

Figure 4 shows the core catcher. Note, that the core catcher is kept in upright position while not engaged by a small spring placed at the center of the tool. This spring has been introduced after experience with the deep drill : At times, we had core breaks leaving a slanted surface. With core catchers in horizontal position, they would turn into the side of the slanted top of the core when the drill started to rotate in the next run. The skew side of the ice core would then break reducing core quality and with a high probability of a lost run.

Figure 5 shows the core catcher in upright and engaged position. The diameter of the ice core is 78 mm, and the diameter of the hole 104 mm. The clearance between the lower part of the drill head and the core is 0.5 mm, the clearance between the inner core barrel and the ice core is 1.0 mm. The wedge angle of the core catcher is 30°, the rake angle is reduced from the 45° used for the bits to 35° making the core catchers less aggressive. But again, the core catchers are as sharp as possible.

HAND AUGER

A hand auger has been constructed using the same components as the shallow drill. The drill head is the same, the dimensions of the core barrel are unchanged except for the length that is reduced to 1.2 m. The handle, rods and clamp between rods and core barrel are the same as used in the swiss hand auger (Rufli, private communication), and are commercially available in Switzerland. Thus, the core diameter is the same as for the shallow drill, simplifying logging and storage of ice cores. The hand auger is normally used for drilling cores of 12 m length. If deeper cores are needed, the shallow drill is used as it can recover several 25 m cores in one day.

CONCLUSION

During its twelve years of service, the danish shallow drill has just undergone few changes. The key changes are the use of aggressive cutters and the use of pitch controlling shoes. This has reduced the power consumption to around 200W, and made it possible to drill a vertical hole.

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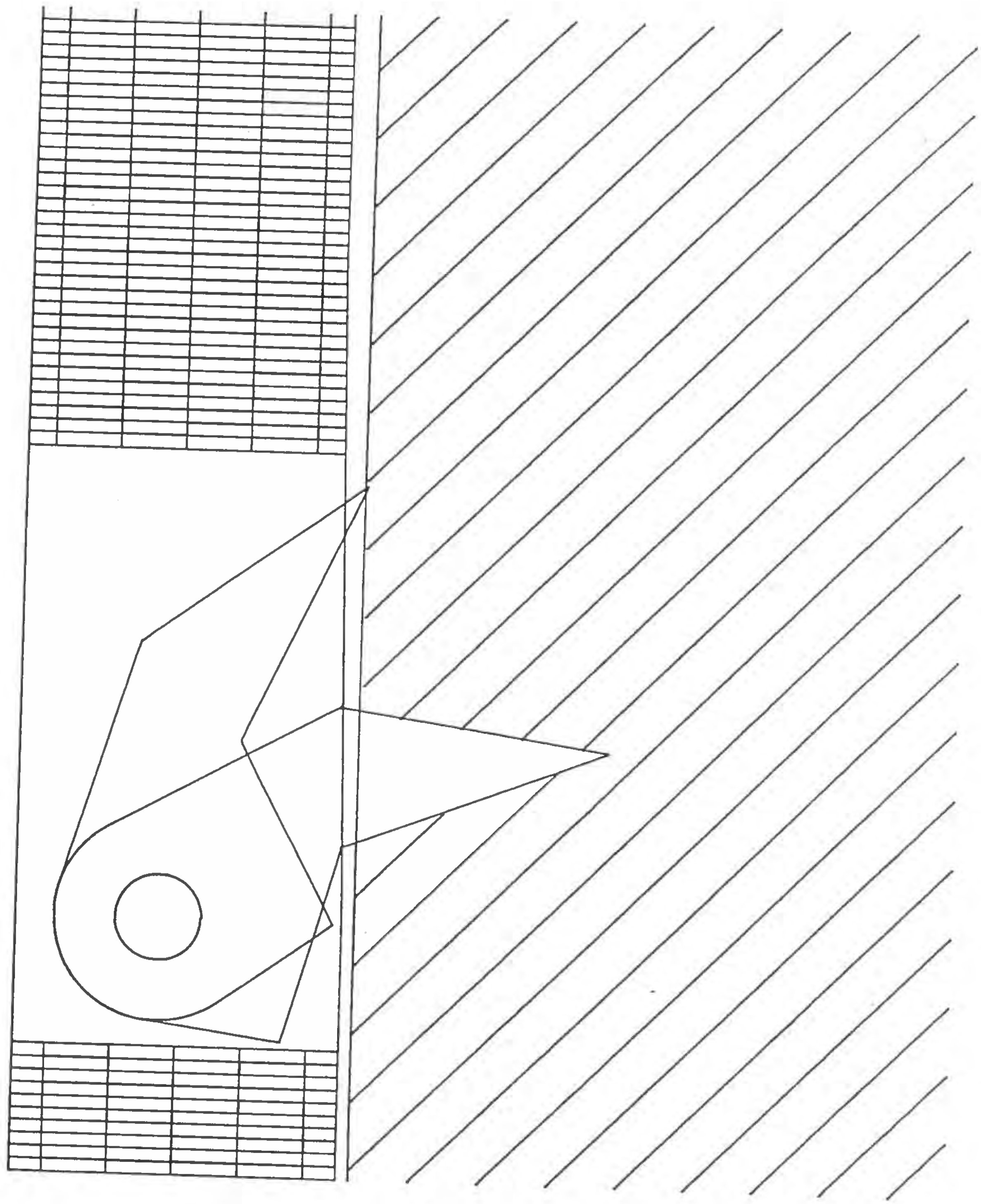

Figure 5 - View of core catcher in normal and engaged position. The distance between ice core and lower part of drill is .5 mm, between inner barrel and ice core 1 mm. The clearance between drill head (or outer core barrel) and hole wall is 1.2 mm.

PERFORMANCE OF THE UCPH SHALLOW - AND HAND AUGERS

by

Clausen, H.B., Gundestrup, N.S., Hansen S.B. and Johnsen S.J.
Geophysical Institute, Haraldsgade 6
DK-2200 Copenhagen N, Denmark.

ABSTRACT

The UCPH shallow drill is intended as a fast drill, operating to depths between 25 and 100 m. A 25 m core can be retrieved in 4 hours, and a 100 m core in one day. The maximum obtained depth is 325 m, with a decreased drilling time for depths higher than 100 m. At depths deeper than some 130 m the core fractures. The core quality was improved at depths below 200 m, by applying a smaller pitch. This created fine chips which enhanced the risk for the drill to get stuck.

INTRODUCTION

UCPH made their first version of the Rand-Rufli shallow drill (Rand, 1976) for the 1976 field season. The drill employed cutters with a 30° rake angle (Mellor, 1976), and a knife antitorque section (Rufli and others, 1976). The drill worked well in a test in South Greenland at Dye 3. Later in the season the drill was lost on the Hans Tausen Ice Cap in Pearyland, North Greenland. The drill was lost mainly due to :

A) The stainless steel outer barrel became slightly banana shaped for unknown reasons.

B) The knife type antitorque section did not provide sufficient antitorque in the heavily layered ice.

C) The cable was attached to the antitorque section without a rotating slip ring section.

After that season, a new version of the drill was developed (Johnsen and others, 1980), and in 1977, five 100 meter cores were obtained. After the ISTUK deep drilling, the drill head was modified (Gundestrup and others, this volume), and the drill has until 1989 augered 26 cores with an accumulated length of 2110 meters. The deepest core is 325 m. The drill has only been used on cold glaciers, i.e. in ice temperatures between -15°C and -32°C.

DRILL HANDLING EQUIPMENT

For holes up to 100 meter, the drill is normally mounted on a 12' Nansen sledge (Fossum skifabrikk, Norway). Thus the set up time is reduced to around one hour. A key point is to reduce the ground time to a minimum, not just to save time, but also to avoid heating of the drill by sunlight. The drill is normally used directly at the surface without drill pits and shelter. Also, the drill components must not be exposed to direct sunlight on the snow surface otherwise snow sticks to the drill. A small rack is placed a few meters from the drill, and the inner core barrel is placed there when the core is extracted.

The inner core barrel, the drill head and coupling to the drill motor are cleaned with a brush and pressurized air. Solvents are not used, as remnants of solvents may cause refreezing in contact with snow down bore hole. If the hammer section in the antitorque section needs to be cleaned, it is heated to around 100°C for some hours, and the drilling is resumed when the drill again is cooled to below the freezing point.

Our main generators are two 3 kW Bosch generators purchased in 1976, one serving as abackup. We have now purchased a 4 kW MASC generator as backup.

If the drilling takes place inside a tent, a modified (oversized) tourist type tent of aluminized nylon is used. Although this tent is a bit weak, it has survived several snowstorms.

CORE PROCESSING EQUIPMENT

The cores are cut into 55 cm lengths, bagged and put into the storage boxes : moulded commercial freezer styrofoam boxes. These boxes are insulated with 5 cm of styrofoam, and the inside dimension are 60*50*60 cm. Empty space is filled with cold snow to prevent the cores from moving during transport. The maximum weight of a full box is 90 kg.

If a 25 m core is drilled, and the air temperature is well below 0°C, all ice cores are placed on the surface shaded against the sun : No core processing takes place during drilling. When the 25 m of core is recovered (2 h) an accurate depth measurement is made, and the cores are then cut based on this numbering scheme : bag 1 spans 0 to 55 cm, bag 2 55 to 110 cm etc. The key point is, that the bag number is a depth reference. If there is a core break within 3 cm from the bag limits, the core break will be used instead of cutting the core exactly at the 55 cm limit, thus we are sure to avoid cumulative errors. The cores are cut after carefully fitting each core break. The drilling ends with a 2 m hand augured core overlapping the upper part of the 25 m shallow core.

When the cores are bagged in a shaded area, they are placed in the freezer box within minutes, because the clear plastic bag acts as a very efficient solar energy collector. If a bagged core is left in the sun for just a few minutes, the surface conductivity signal on the outer layers of the ice core is destroyed.

When cores are drilled to greater than 25 m, 3 drillers are normally used, two are drilling, and one takes care of the processing of the core. Normally, no measurements are performed in the field except for density measurements, however at times, the Laki eruption is identified by measuring surface conductivity. This eruption is a major marker at the 100 m depth range, and it is essential, that cores are sufficiently deep to span this eruption to insure a fixed point on time scale of the ice core.

EXAMPLE OF A SHALLOW DRILLING EXPEDITION

As part of a joint american-swiss-danish effort to locate a suitable deep drilling site in Central Greenland, a team of 3 was put on the ice by a US C130, June 30, 1985. The total weight including 3 heavy "skidoo's", 6 Nansen sledges and 600 liters of mogas was 4000 kg. During a period of 16 days, the team travelled 120 km, made 5 camps recovering a core at each site. Three 100 m cores and two 25 m cores were recovered. By July 15 everything was packed and the team was ready for pick up.

CORE QUALITY

Up to a depth of 130 m, the core quality is very good with literally no fracture. At 140 m, we experience breaks originating from the core catchers and running along the length of the core. Also, a few breaks perpendicular to the core axis start to form. On the Renland Ice Cap in East Greenland, we went deeper, and around the depth of 250 m, the core tended to create wafer type breaks similar to those experienced with thermo drilled cores. In order to preserve core quality, the pitch was reduced to 3 mm. This reduced the chip thickness to 1 mm. This stabilized the core quality somewhat, and it was decided to continue with the low pitch in spite of the problems introduced by the fine cuttings. The fine cuttings are dificult to transport up the auger flights, and they tend to stick to the surfaces. This is a real threat to drilling safety because we had to use the hammer frequently in order to move the drill downwards, and also to use the hammer while breaking the core. Both problems are caused by chips which are not collected inside the drill, and which stuck to the hole wall. Finally, close to bedrock (fine clay particles in the core), we were not able to break the core, and the drill was stuck. The problem here was simply a very tough ice as the drill was not wedged in - it could be moved around 10 cm. In order to free the drill, 20 liters of a 30 % glycol/water mixture was dropped down the hole through a 50 m long plastic tubing. The mixture was not heated, because it would have cooled down before reaching the drill 325 meters below. The next day, the drill was free and used to recover another 90 cm long core.

SPECIFIC ENERGY

The specific energy (the energy required to produce 1 m^3 of cuttings) and motor current, using the modified drill head described by Gundestrup and others (this volume), are estimated to be :

	100 m	250 m	325 m
MJ/m3	3.4	7	9
I [A]	1.8	2.8	3.4

For the ISTUK deep drill used at Dye 3 in South Greenland, the specific energy was around 5 MJ/m^3 at 500 m and around 16 MJ/m^3 at 2000 m (Gundestrup and others, 1984, 1985). Thus, in spite of the fact that ISTUK was operating in a liquid filled hole, the cutting energies are comparable.

PENETRATION RATE

A 25 m drilling, including setup, repacking and moving the drill 5 km to the next site, takes 4 hours. For deeper drillings, figure 2 shows depth versus drilling time. The time used is the actual time spent on drilling, including set up, erection of drill tent, repairs etc. It is interesting to note, that the penetration rate is around 300 m/week, independent of depth ! The reason is, that the time added by moving the drill up and down the hole is compensated by the experience gained by the drillers. For the deepest drilling, the penetration rate even increased below 180 m ! The reason is, that the drill team was increased to 4 people which made it possible to extend the drilling time to 16 hours a day using two shifts.

The **hand auger** was used at Camp Century (Gundestrup and others, 1987). Here, 44 cores with an accumulated length of 358 m were recovered by two of the authors in 5 days when they awaited a pickup. Only a few of these cores were processed - most were discarded.

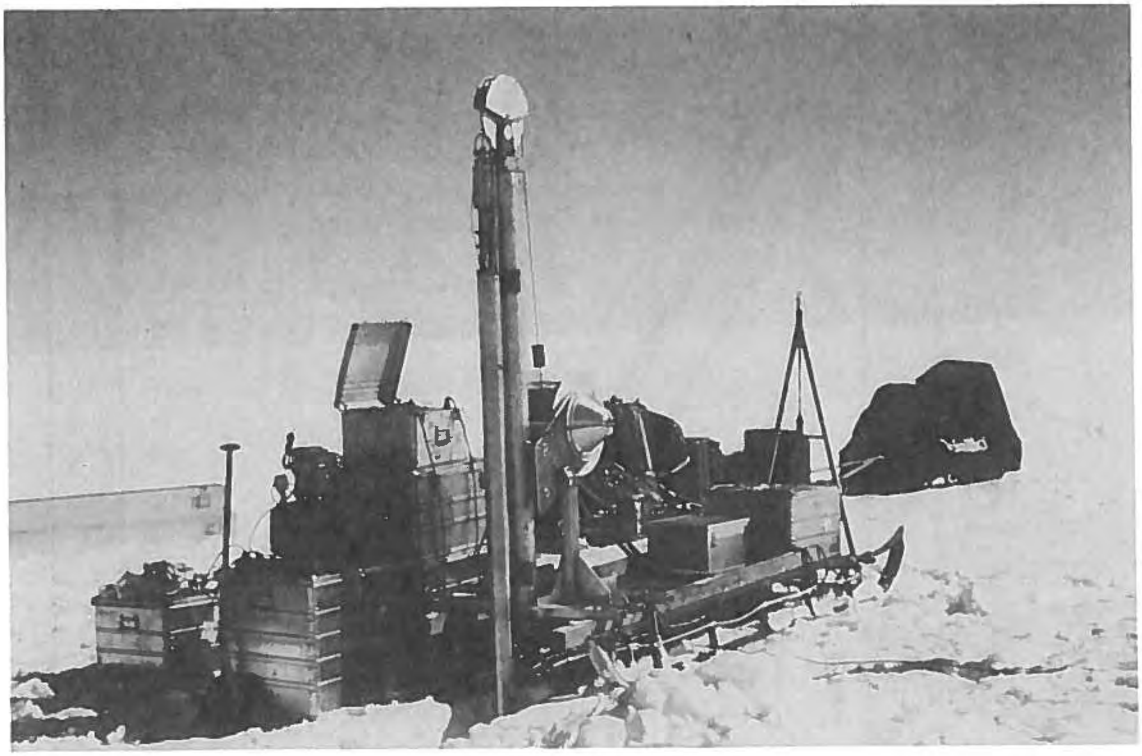

Figure 1 - Drill set up as used in Central Greenland. The tiltable "tower" in mounted on a 12' Nansen sledge. The console is placed on top of a transport box.

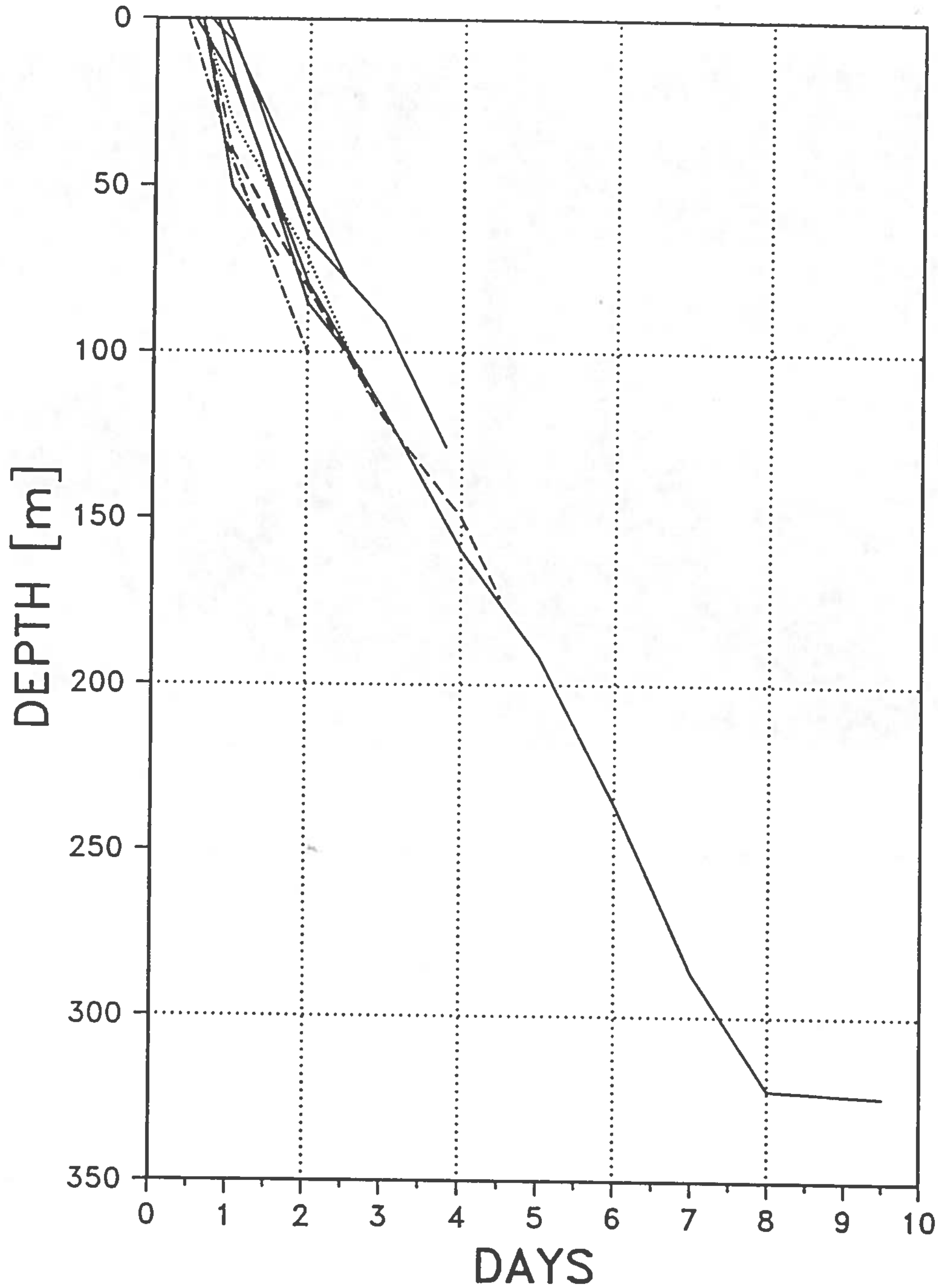

Figure 2 - Time of day versus depth for 8 shallow drillings. The time used includes set up, repair, erection of tent etc.

SUMMARY OF UCPH SHALLOW DRILLINGS

The shallow drill has been used to recover the following ice cores :

1976	Dye 3	100 m
	Hans Tausen	60 m, drill lost
1977	Dye 2	100 m
	Camp Century	100 m
	Camp Century upstream	70 m
	North Central, 1	100 m
	North Central, 2	102 m
	North Central, 3	107 m
	North Central, misc	2*25 m
1978	Dye 3	100 m
1983	Dye 3, 4B	174 m
1984	Dye 3, 18C	113 m
	Dye 3, misc	5*25 m
	Central Greenland, D	100 m
	Central Greenland, B	100 m
	Central Greenland, C	25 m
1985	Central Greenland, E	78 m
	Central Greenland, F	25 m
	Central Greenland, G	71 m
	Central Greenland, H	26 m
	Central Greenland, A	129 m
1988	Renland, long	325 m
	Renland, short	90 m

Total 26 cores, 2110 m of ice with same drill, same cable.

Since 1976, the drill has remained almost unchanged with the exception of changes to the drill head. The cable is that purchased in 1976.

FUTURE CHANGES

No change to the set up is planned except for a possible modification to the drill head incorporating the small cutters in front of the main cutters to facilitate freeing the core. This change is inspired by the swiss group (this volume). Also, the controller should be replaced by a hermetic version. The shallow drill will be duplicated in order to have a backup version.

ACKNOWLEDGEMENTS

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NEW DIRECTIONS IN DRILLING AND RELATED ACTIVITIES

by

B. Koci
Polar Ice Coring Office
University of Nebraska-Lincoln
940 North 17th Street
Lincoln, Nebraska 68588-0640, U.S.A.

ABSTRACT

This paper will deal with ways of improving drill performance using new material technologies and project improvement through use of lightweight shelters and improved core processing.

Composites play major role in continuing improvements by allowing increased design freedom. Areas of particular interest are anti-torque springs, drill barrels, and hand auger extensions.

New, stiffer cutting heads with tungsten carbide or synthetic diamonds significantly reduce cutter wear and are cheaper to produce than standard tool steel cutters. Standard rock drilling technology as applied to increasing sample size through interesting areas will be discussed.

The use of high pressure fluid to cut cores can significantly reduce contamination and provides a finished surface for analysis. Cutting swath is limited to less than 0.5 mm.

INTRODUCTION

When one mentions new technologies applied to drilling it often means applying proven technologies in new ways to answer new questions that arise. The new analytical techniques for ice chemistry require core that is tree of contamination and of better quality than previous samples. In addition the need for more and better samples of subice material has become apparent.

The question is how do we go about addressing these needs and what mechanisms or processes are available to allow the design freedom necessary to get access to the material.

It is essential to understand the process that occurs at the drill bit/ice interface. Cutter and core breaking geometry are at this point known for ice . We also know that round, straight tubing for the barrels and cutting heads that remain true are critical components in maintaining any hope of collecting good quality core beyond 150 m.

We are currently working with NOR Industries of Pawhuska, Oklahoma developing heads and cutters made of sintered material.

Heads can be made of sintered tungsten which remains round and will not easily be damaged by drilling or transportation. A typical 10 cm cutting head weighs nearly 10 kg which is desireable since keeping the weight low on the drill helps keep the hole straight.

Cutters and penetration shoes can be made of sintered tungsten-carbide which should drill many holes without sharpening. A complete ring of cutters and penetration shoes can be made for under $300 and because of the manufacturing process should be nearly perfect.

When entering the subice material this ring can be replaced by cutters more suitable for rock drilling provided the drill is heavy and has enough power to grind up rock. The mining industry and bit manufacturers such as Eastman Christiansen have the most advanced technology rather than the oil drilling industry.

Kaiser Rollmet of California has come up with a process for making tubing that is round, straight, and concentric. Their process involves roll forming the tube rather than drawing it which assures all of the above. While the cost of this tubing approaches $1,000/m, it comes inspected and nearly perfect. An added benefit is that the tubing is custom made. Hence it can be ordered to any size and thickness designed, increasing drill design flexibility considerably. Virtually any formable material can be used.

Experience has shown that we increased the core quality considerably below 150 m when we began using this tubing. The added benefit of being able to use all material supplied without rework, knowing that each of our drills is identical has strong merit which I believe overrides the cost factor.

Another consideration is the use of composite barrels which again because of the process are assured to be round and straight. In this case weight savings is not a consideration.

Flites can be wound onto the barrel as an integral part of the assembly and can be put on the inside of the outer barrel allowing the inner barrel to remain stationary.

In addition, a taper can be formed on the inner barrel allowing easier extraction of the core. Current wisdom suggest a taper of 0.25 mm/m.

Chemical inertness, low coefficient of friction and smooth finish add to the desirable qualities of this process.

These barrels can be made by ADDAX of Lincoln, Nebraska, a manufacturer of torsion shafts.

This past summer a set of extensions for the PICO hand auger made of graphite and Spectra was tested in Greenland. Their weight is 360 grams/m compared to 1,100 grams/m for the glass epoxy extensions currently used. The new extensions will survive torque and tension generally beyond human strenght. Their cost is approximately $100/m compared to $56/m for the standard water pipe extensions. They should allow expansion of the drill system to depths beyond 50 m which is especially important in high alpine areas of the planet.

When drilling deep cores greater than 1,000 m, there are depths where additional core material would be helpful. it is worthwhile noting that sidewall coring devices are available or a triangular piece can be cut out of the hole wall. Either of these samples can be placed in a pressurized container for time critical studies. Drilling additional holes off the main hole should also be considered since it too is standard a rock drilling technique.

Having retrieved core how is it best processed ?

A technique developed to cut composites and abrasive materials may be applicable. High pressure fluid (perhaps drilling fluid) forced through a small nozzle (less than 0.5 mm) under high pressure (3,000 bars) can be used. The cutting rate of ice should be high and the surface after cutting will be polished. Since a fluid is used there should be little contamination of the core and the absence of vibration should help keep the core in tact through the brittle ice zones. Experiments on cores will proceede in the spring of 1989.

Since the machine of the processing can be done in an enclosed area limiting the contamination as well as exposure of the processors to noxious drilling fluids. Samples for chemical analysis can also be taken with a measurable degree of cleanliness.

The drawbacks are cost of approximately $100,000 and high power requirements which approach 20 kw.

CONCLUSION

A lightweight dome was successfully tested in Greenland this past summer. Using 2033 aluminum alloy weight for the 6 meter dome is 60 kg. Struts and hubs are shown in Figures 2, 3, 4 and 5. In addition we have been using Moss Optimum series tents with good results. Both shelters provide a drift free zone around them.

The conclusions of this paper are more appropriately presented at the next symposium.

ACKNOWLEDGEMENT

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DESIGN AND LOGISTIC REQUIREMENTS FOR ICE CORING AND SAMPLE RETURN FROM REMOTE HIGH ALTITUDE LOCATIONS

by

B. Koci
Polar Ice Coring office
University of Nebraska-Lincoln
940 North 17th Street
Lincoln, Nebraska 68588-0640, U.S.A.

ABSTRACT

Ice coring and sample return from remote locations above 5,000 meters accessible only by foot or pack animals presents some interesting design challenges. Projects in Peru and China have demonstrated that good quality cores to bedrock can be retrieved and samples returned in a frozen state for detailed laboratory analysis.

A description of the drilling systems, power sources applicable to high altitudes, and equipment/core packaging for long rough journeys will be considered.

Electromechanical and thermal drilling systems will be discussed along with the use of composites, solar, wind and mechanical generation systems.

INTRODUCTION

During the 1984 Drilling Symposium in Calgary, I proposed a drill system based on the use of Kevlar reinforced electromechanical cable and lightweight components that could be dissassembled for use in remote areas of the world. A limit of 25 kg for any single piece was established to allow for backpacking equipment into remote mountain areas. This equipment is also robust enough to handle drilling conditions and the cold ice of Antarctica.

From a design standpoint, a way of reducing core break from over 2,000 kg force to under 100 kg was the first requirement. The second requirement was to reduce cable weight without creating high resistance in the conductors to allow use of thermal or electromechanical drills. The third and fourth requirements were to keep power generating equipment manageable and provide light yet comfortable shelter for living and processing core.

In 1979, an attempt to drill a 100 m core on the Quelccaya Ice Cap in Peru failed because a helicopter could not carry equipment to the summit. Since the equipment was too heavy to backpack attempts at drilling were abandoned.

As a result the PICO hand auger was developed to push the coring capability deeper while a more portable system was developed. A primary consideration was that this system had to be robust enough to handle much colder ice in Antarctica and Greenland.

In 1981 drilling at South Pole using

inefficient coredogs to break the core caused breaks approaching 3,000 kg with 10 cm core were experienced. Efficient core breaking devices were developed and successfully tested the following season reducing the core break to less than 100 kg.

Once this was demonstrated the way was clear to use kevlar reinforced electromechanical cable, reducing the cable weight by a factor of three. This made it possible to reduce mechanical requirements to a point where all the mechanisms involved could be kept under 25 kg. Thus the system could be trasported anywhere a person could walk.

This system was successfully used in 1983 on Quelccaya to drill two holes of 163 and 154 m to bedrock at an altitude of 5,700 meters. During the summer of 1987 the system was again used on the Dunde Ice Cap in China to drill three holes to bedrock at 135 m. In the same time period similar systems have been used in Greenland and Antarctica to collect nearly 1000 m of core annually in boreholes to depths of 300 m.

Flexibility is the key to design of this system. Since permanent magnet DC motors are used throughout many power sources from solar to engine driven generators are available.

Solar power is the favorite since it does not contaminate the area, is noiseless, and requires no maintenance. It also does not work on stormy days when one should not be drilling anyway.

Solar panels can be expected to provide from 110 to 130 % of their rated performance largely because of reflected light from the snow surface and increased efficiency in colder climates. This is indeed refreshing compared to a 50 % decrease in engine driven generators at the 5000m level.

A standard set of reversing switches rated to twice the expected voltage should be considered since decreased atmospheric pressure increases likelihood of arcing. The addition of a variable resistor provides the necessary motor speed control. There is no need for batteries or any electronic widgets rendering the system virtually indistructable.

Since renewable energy sources are desirable from a standpoint of no contamination windpower is always a consideration. Of the many types of generators available, the vertical axis wind turbine is an example. Few areas of the planet have the favorable steady winds of 30-60 km/hr. The technology is off the shelf but siting is a problem.

The least desireable but sometimes necessary use of engine driven generators is inevitable. Because drilling on Dunde was done in the stormy season, a single cylinder ultralight two cycle engine made by Rotax was chosen to drive a 5 kW alternator. This engine is rated at 20 kW at sea level which extrapolated to the 500 mb level is 10 kW. The system functioned flawlessly and arcing in the generator was not a problem.

In this case the AC voltage was varied using an auto transformer, then rectified with a bridge diode. To date we have experienced no failures with this system despite the low inductance of the DC motors.

Two drill types have been used, on thermal and the other electromechanical. Since ice caps at low latitude, high altitude locations are generally warmer than -10°C, both give good quality core.

The thermal drill used on Quelccaya consists of a ring of stainless steel 5 mm thick which has several wraps of hermetically sealed heater brazed to it. This heater is 1.2 mm in diameter and can dissipate in excess of 50 W/cm. Since the heater length in this case was 2 m over 8 kW could be dissipated. In a 10 cm ring 5 mm thick. At 4 kW film boiling begins to occur around the heating element limiting the power.

The robust nature of this heater is demonstrated by the fact that the heater and core barrel were dropped several feet onto concrete but continued to function through the entire season and is still functional.

A pressure test of the heater was conducted demonstrating a capability of surviving 1,500 bars of pressure suggesting no theoretical limit to its depth capabilities. Since the rest of the drill is a 5 mm thick 10 cm tube, there is nothing to limit the depth capaility.

A standard PICO electromechanical drill was used on Dunde in 1987 providing good core and 100 % recovery to the bottom. The only change required was to increase penetration rate to 1.3° from the normal 1.2° to compensate for the warmer ice.

More extensive use of composites in the drill barrels would aid in the transportability of this drill. This is mainly a consideration because of their ability to resist damage when encoutering rocks.

Packaging equipment for transport by horse or man is interesting. Generally the packaging must be light, strong and humane. Hardigg shipping containers made of polyethylene meet all the above criteria. Generally size should be limited to 60 cm x 20 cm x 60 cm for comfort to the animal.

Solar panels were packaged in canvas bags padded by 2 cm of foam protected on the outside by .5 cm plywood. This provided protection adequate for the panels to survive being rolled on by the horses.

Retrieving ice core from remote areas as ice core has become a reality. To do so means keeping it below freezing for periods of up to 5 days in 30°C heat.

Insulated Shipping Containers of California supply boxes of expanded polyurethane foam bonded to cardboard inside and out. The bonding process provides a trong and lightweight box that can be tied a horse with 50 kg of core and survive the trip.

The addition of a eutectic mixture such as blue ice around the core tubes provides a cold storage mechanism twice as effective as dry ice. By choosing a mixture that freezes at -5°C the material can be frozen at night on the glacier surface in preparation for the return trip.

Using the above mechanisms, 100 m of ice core was successfully returned to Ohio State University for analysis.

CONCLUSION

We have shown that it is possible to work in high altitude remote environments and retrieve good quality scientific ice core samples. Additionally, it is possible to retrieve these samples from the field in a frozen state and return them to the United States for analysis.

To do so requires a multidisiplinary approach and a lot of experience to cope with the different conditions in ice and environment. With available equipment it appears that a practical system limit is 7,000 m with an engine driven generator and unlimited with solar power. The only limiting factor is human performance which, at that altitude, remains unknown.

Low tech solutions generally are the best performers. Simple systems are required since the investigating team is working near the edge of human performance with potentially dangerous machinery.

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DESIGN OF A DRILL TO WORK IN A FLUID FILLED HOLE

by

B. Koci
Polar Ice Coring Office
University of Nebraska-Lincoln
940 North 17th Street
Lincoln, Nebraska 68588-0640, U.S.A.

ABSTRACT

Since core quality rather than hole closure limits the maximum depth capability of a dry hole, we are constructing a modular drill compatible with a dry drill to work in a fluid.

Use of standard industrial equipment such as sludge pumps and well screen keep the cost of this drill relatively low. Because of its robust nature, this drill should also be able to penetrate subglacial material.

Results of the test this summer in Greenland wil be presented.

Suggestions for drilling fluids and their relation to personnel, environment, and core quality will be considered.

INTRODUCTION

Since core quality rather than hole closure limits drilling depth man open hole the logical solution is to add fluid to compensate for overburden pressure. The fluid also aids the drilling process by enhancing chip removal and damping vibrations in the drill.

The current drill design is based on incorporating pumping and filtering mechanisms in an existing dry drill design. Core size has been increased to 13 cm so a greater volume of ice can be retrieved in each sample.

An instrument package has been incorporated in the drill to monitor drilling progress and will be upgraded to provide a feed back loop that will assure smooth penetration control (Hancock, 1988).

Selection of a drilling fluid is still underway since chlorinated hydrocarbons are toxic as well as potential sources of contamination for many of the ice chemistry analysis. See Appendix A for selection criteria.

In 1984, a practical limit to open hole drilling was reached in the 200-300 m range. Beyond that depth the ice becomes brittle, largely due to high bubble pressure in the ice. One can only go so far in perfecting the drilling process before solutions become too costly.

Addition of a hole fluid to compensate for the overburden pressure helps by decreasing the defiance of basic physical laws. Additionally chip removal is done gently rather than by the brute force technique of spiral auger flites. Another benefit is the lubrication provided between ice core and barrel as demonstrated by tests this past summer in Greenland.

Past experience drilling in ice saturated by water has demonstrated that current dry electromechanical drills will work in an ice/water slurry and recover good quality core. Extrapolating to a diesel fuel/ice clurry thus becomes a reasonable choice. All that is needed is to pump less than 10 % by volume of chips into a filter where the excess fluid is extracted and returned to the drill hole.

Rather than worry about pumping slurries of narrow viscosity ranges, a pump that can handle a wide range of viscosities was selected. In addition a pump that works in the long axis of the drill makes design much easier. Hence selection of a progressive cavity Moyno pump becomes the choice. This pump handles anything from air to peanut butter as well as chunks of material with no clogging or damage. The only penalty is a power requirement approaching 1,000 W to overcome friction caused by deforming the stator. Pump and drill operate in the same rotation speed range of 60-150 rpm. Since the drill produces about 4 liters of chips per minute a 40 l/min pumping range is desirable which suggests an outer diameter of 16 cm. Thus the selection of 13 cm core size.

The filtering mechanism is borrowed form the water well industry. Johnson stainless steel well screens with a gap of 0.2 mm filter out sand and clay size particles with no pressure drop across the screen. This screen is robust, straight and sufficiently strong to be incorporated directly in the drill with no added support structure.

Tests in the field and test wells have shown that both the pump and screen perform as expected. The pump will handle ice chunks and the screen filters the finest snow particles with no evidence of any particles passing through.

A schematic of the drill appears in Figure 1 giving general locations of components. Core barrel and screen length can be varied to suit the application. Maximum length of each is approximately 5 m which seems adequate for drilling to 3,000 m.

A high pumping rate and open system design allows drill design to proceed without need for seals of any kind. A few leaks are acceptable. Likewise the motor and gear reducer sections are allowed to fill with fluid. Tests of 100 hrs operating in DFA has shown no degradation of motor performance.

Mechanical portions of this drill are perhaps easiest to design. The addition of a navigation package is one of the design features of this drill necessary to keep track of drilling processes once drill depth has reached a point where the thumb on cable method is no longer adequate. A presentation of the capabilities of this package and suggestions for future updates will be presented later in this symposium.

Good penetration control is essential to good core quality. At depths beyond 1,000 m we feel that a feedback loop will be necessary to balance weight on bit, penetration rate and torque to drill head. Because of cable elasticity, current wisdom suggests accomplishing all this on the drill rather than trying to work it through a winch driven system. The exact method is unclear yet.

Drilling deep core will also require taking oriented core for physical properties studies. By monitoring drill orientation with a fluxgate magnometer and relating that to drill barrel position through an angular transducer, the process is straight forward. Marking the core will be accomplished by marking one of the core dogs.

Currently a 1,000 m winch is used to work with this drill. This winch weighs 700 kg complete and can be moved with two skidoos. Thus core can be drilled into new scientifically interesting areas without the need for heavy support equipment.

A 15 kW Lister diesel generator set turbocharged to provide sealevel power to 20,000 ft was used this past summer with no failures. This was coupled to a 15 kw permanent magnet Dc motor through auto transformers, a bridge rectifier and a choke. The system is capable of pulling over 1,000 kg without any evidence of weak links.

The cable, supplied by Cortland Cable of New York has four # 18 power conductors and three # 24 signal conductors. A 5,000 kg strength member is consistent with a working load of up to 500 kg or 1/10 the breaking strength. Since the wires are all spark tested to 3,000 VDC and sliprings rated to 1,000 VDC there are no anticipated weak points in a system designed to work at 560 VAC.

To compensate for increased cable length, voltage is stepped up to a maximum of 560 VAC for transmission through the cable. Toridal transformers located above the drill reduce the voltage to make it compatible with the motor windings. After stepdown the AC is converted to DC and run through on inductor to improve the quality. Reversing switches are also incorporated as part of the downhole instrument package.

RESULTS

As expected, 13 cm core is more robust and generally superior to 10 cm core. This is largely due to having more volume to resist forces generated by drilling and relief of the overburden pressure. Because of the efficiency of the core dogs little additional force is required to break the core at the end of a drilling run.

The 13 cm diameter core is easy to handle and work with provided length is kept to the 1 m range. There is less likelihood of core breakup during processing and it appears there is enough core to support two investigators with one core thus reducing drilling requirements considerably.

Tests in the PICO test well and pumping and filtering tests performed in the field have demonstrated the ability of the pump and filtering mechanisms to perform their tasks. The drill and screens now can be scaled up to a length that will allow retrieval of three meter cores first then six meter cores. As always more testing is required but to date there are no surprises.

CONCLUSION

13 cm core is a reality in dry or wet versions. The question now is how deep and should we consider 15 cm core ?

ACKNOWLEDGEMENT

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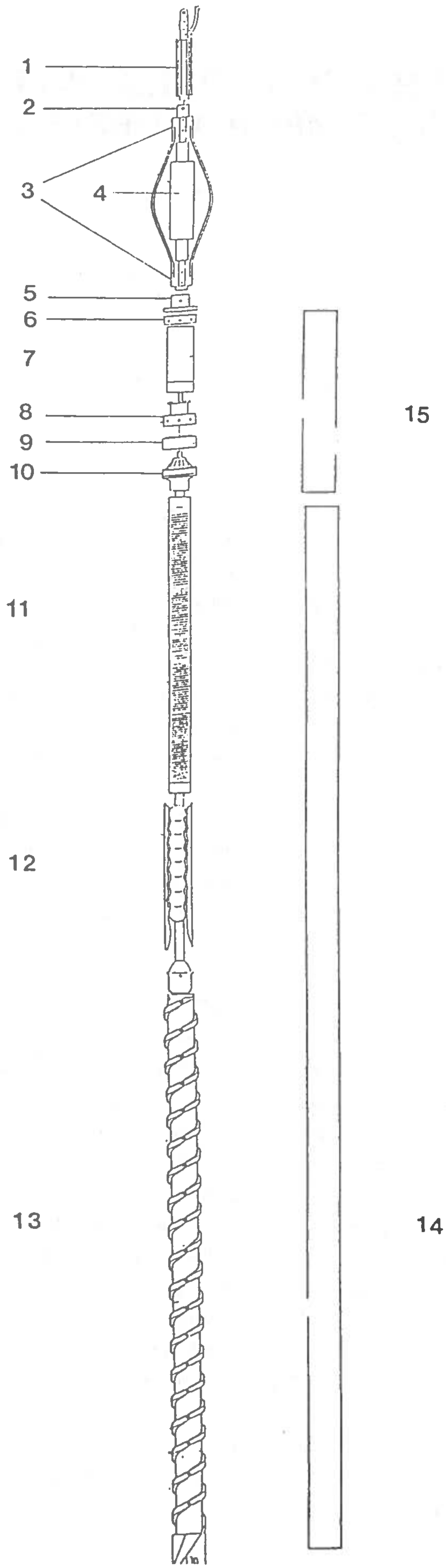

Fig 1.

1 slip ring
2 anti torque tube
3 sliders
4 instrumentation package
5 antitorque support
6 motor tubing end
7 motor
8 4" drill adaptor
9 input side flange
10 gear reducer
11 Johnson well screen
12 Moyno pump
13 inner barrel
14 outer barrel
15 outer can

ELECTROMECHANICAL DRILLING IN DRY HOLES TO MEDIUM DEPTHS

by

J. Schwander and H. Rufli
Physics Institute
University Bern
Sidlerstasse 5
CH-3012 Bern, Switzerland

ABSTRACT

The maximum depth for ice core drilling in dry holes is limited due to bore hole closure by the action of the hydrostatic pressure and the difficulty to obtain unbroken cores below a certain depth. In this paper we discuss the various sources of stress that act on the core and the consequences for the design of mechanical ice core drills. We present the latest version of our mechanical drill system which has been modified to produce better cores from greater depths.

INTRODUCTION

According to the maximum depth reached by ice core drilling one distinguishes usually between shallow and deep drilling. Shallow drilling comprises operations down to or slightly below the firn to ice transition, i.e. to depths on the order of 100 meters. Due to the short drilling time and the relatively low hydrostatic pressure at these depths bore-hole closure is not a problem and hole fluids are not necessary. Deep drilling to depths over 500 meters however usually go on for several weeks or longer and bore-hole closure must be prevented by filling the hole with a liquid. The use of bore-hole fluid increases the complexity of a drilling system and the logistics considerably. The hole fluid is also a potential source of ice core contamination with trace substances and may even change the gas composition in the bubbles. It is therefore desirable to extend the maximum depth of dry drilling as deep as possible. Bore-hole closure sets a practical limit to the maximum depth can be reached, although this limit can be pushed out with an adequate drill design. Core drilling to intermediate depths was also often not very successful because below a certain depth the ice cores were more and more fractured.

FACTORS LIMITING THE DEPTH FOR THE PRODUCTION OF GOOD QUALITY ICE CORES

- ***Bore-hole closure*** : Since there is essentially no clearence between the cutters and the bore-hole wall already a slight decrease of the hole diameter increases the friction between the drill and the bore-hole wall considerably. Johnsen et al (1980) have calculated the closure rate as a function of depth and temperature. The results are based on measured first year strain rates of two holes (Byrd Station, Antarctica and Site 2, Greenland). For a hole of 100 mm diameter in ice with a temperature of -10°C, for example, a closure rate of a 0.1 mm/day is reached at roughly 80 m depth whereas at -30°C the same closure rate is observed only at 200 m depth. The maximum attainable depth therefore depends on the ice temperature, the drilling speed and the drill design (cutter - wall contact area).

- *Core fracture* : There are several stress components acting on the core during and after drilling. Some of them grow with increasing depth. The sum of them ultimately causes the core to fracture either during drilling, core break or handling. The major stress sources are :

- air pressure in the bubbles,
- drilling (cutting force and other stresses),
- release of hydrostatic pressure,
- core break.

The maximum tangential tensile stress σ in the ice shell around the air bubbles immediately after the hydrostatic pressure has been taken away (after the drill bits have cut the groove around the core) is $\sigma_{max} = p/2$, where p is the bubble pressure at the corresponding depth (Timoshenko and Goodier, 1970). p is in a first approximation close to the hydrostatic pressure. The maximum comparative uniaxial tension around the bubble is then $\sigma_{uniaxial,max} = 3/2\ p$ (Sayir and Ziegler, 1984), which can be compared with the tensile strength of ice. The tensile strength has been measured by various authors. A review is found for ex. in Hobbs (1974). For polycrystalline ice the values increase from about 1.5 MPa at 0°C to 2 MPa at -40°C. For single crystals values of ca. 10 MPa are reported. It is not obvious which case - single crystal or polycrystal - is more appropriate for our considerations. In the worst case we must expect the formation of small cracks around the bubbles already at hydrostatic pressures above 1 MPa, corresponding to a depth of approximately 140 m. This is indeed the depth where usually first problems with fractured cores appear. It is not clear whether or not this can be attributed to crack formation around the bubbles.

Drilling in a dry hole leads to an almost immediate pressure release in the ice core. This causes two kinds of stresses in the ice. (1) The bottom of the core, still attached to the bulk ice, is compressed by the surrounding hydrostatic pressure while the upper part of the core is exposed to atmospheric pressures. This leads to shear stresses near the bottom of the core. (2) Due to the anisotropy of the elastic modulus of ice internal stresses remain in the ice core after the hydrostatic pressure has been taken away.

The drilling itself also exerts forces on the core. All but forces from the cutting of the ice are in principle avoidable since the core when still attached to the bulk ice must not have any contact with the core barrel or any other part of the drill. In reality however it can hardly be avoided that some ice chips get between ice core and barrel and exert a small torque on the core. But with a well designed drill this is a minor problem. The forces on the core from the cutting mainly depend on drill head parameters like pitch, rake and clearance angles, cutting speed, cutter geometry etc. and can be minimized by an appropriate design.

Core catchers have generally a wedge-shaped form in order to break the core when pulling the drill up. This causes a strong stress concentration at the tip of the core catcher and often leads to longitudinal or skew core breaks at depths where other stress sources are already important.

CONSEQUENCES FOR THE DESIGN OF MECHANICAL ICE CORE DRILLS

From the above-mentioned considerations on the stress sources a mechanical ice core drill for dry holes must meet the following essential requirements :

- Overall precision and stability to assure no lateral forces on the core, a straight hole and minimal vibrations for a smooth cutting.
- Self centering drill head design for absolutely centered rotation.
- Minimum cutting force on the core side of the drill head by using a small pitch and sharp cutters with a clearance angle.
- At the end of a run the core should not be broken but cut horizontally.

These requirements have been partly realized in the new version of our electromechanical 4 inch drill. The basic design has been described by Rufli et al (1976). The diagram of the new version is shown in Fig. 1. Description of the drill system :

Power requirements	380 V (3 phase), 15 A
Electronic control	Transistorized pulse with DC control for winch and drill
Winch	DC servo motor with reduction gear 4 kW (8 kW peak) 500 m Kevlar cable (11 mm diameter/7 x 0.6 mm^2 copper conductors) speed : -1 m/sec to +1 m/sec (5 % speed stability at 1 mm/sec)
Drill	core diameter : 105 mm hole diameter : 143 mm speed : -120 to +120 rpm typ. power consumption at 60 rpm : 300 W specific energy consumption : ca. 7 kJ/kg of chips
Tower	9 m high with shaft encoder on top wheel for depth measurement

Concerning the overall stability the drill is equipped with a centered anti-torque section (Fig. 1). The three skates that prevent the drill from rotation are machanically forced to be at the same distance from the drill axis. They are retracted during rising and lowering of the drill. They are driven out to the wall by torque and the release of the cable tension.

The drill head is self-centering in the hole by eight 2 mm wide helical lands, one in front and one behind each chips groove (Fig. 2). One land slightly overlaps with the next so that the drill head touches the hole wall on its whole circumference.

A small drill pitch reduces the stress on the core. However the pitch cannot be decreased to any value because if it is too small the chips are too small to be removed by the auger flights. One way to overcome this problem is to introduce small cutters along the core between the main cutters. We designed a drill bit with four main cutters and four small cutters (Fig. 2). At a pitch of 6 mm per revolution each cutter cuts only 0.75 mm. Along the core side a clearence angle is essential. With no clearence angle "wafered" cores cannot be avoided below approximately 130 m depth. The eight lands of our drill bit yield a rather large contact area with the bore-hole wall and are thus not a good solution in respect to the problem of hole closure. We therefore plan to add additional cutters at the upper end of the drill head to enlarge the hole by a few tenths of a millimeter. This way we create enough clearence to move the drill up and down while maintaining a well centered rotation of the drill bit.

The drill has been succesfully tested at Dye 3, Greenland, in June 1988. A core of very good quality was drilled to a depth of 183 m. Pieces of 1 m length could be recovered with each run. At this depth we encountered considerable problems with hole closure. The lowest 10 meters had to be reamed carefully every day to avoid the drill bit getting stuck in the bore-hole.

CONCLUSIONS

The various improvements to the Swiss Electromechanical Drill considerably increased the quality of the recovered ice cores at medium depths. Although these improvements are based on considerations to reduce stress on the core, the design of a drill that produces good quality ice cores under most conditions requires a profound knowledge of all parameters responsible for possible core fracturing. The relative importance of the various stress factors to the core should be investigated carefully. This would enable us to design a drill bit that exerts minimal forces on the core and would probably allow to recover unbroken ice cores from depths of 500 meters at sites with mean temperatures below -20°C. Completely new drill designs should also be investigated : for example high speed cutting with removal of the ice powder by air stream and filters. The development of a reliable horizontal core cutting system instead of traditional core catchers would be very valuable.

ACKNOWLEDGMENTS

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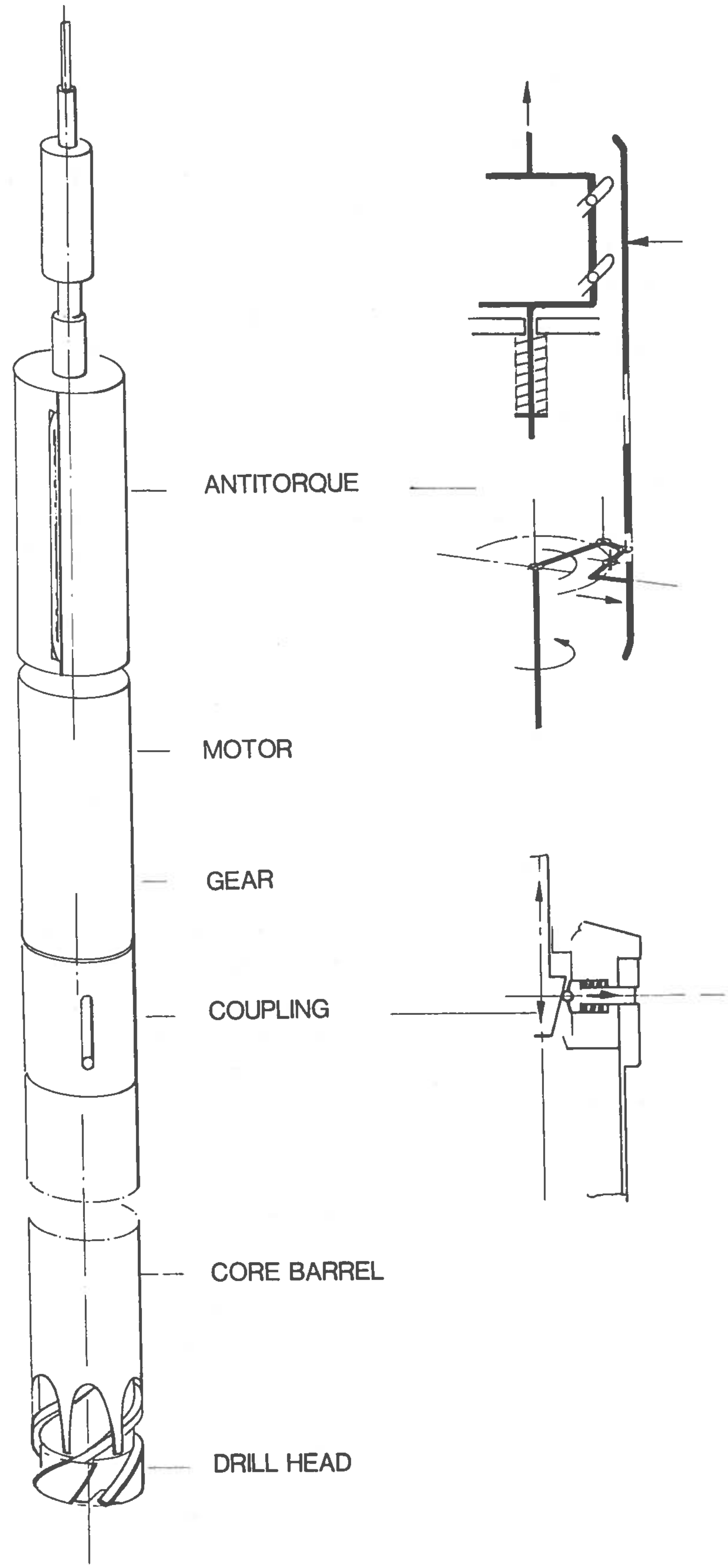


Fig. 1 - The 4-inch electromechanical drill. The operation principles of the antitorque section and the coupling of the core barrel to the drill are shown on the right side.

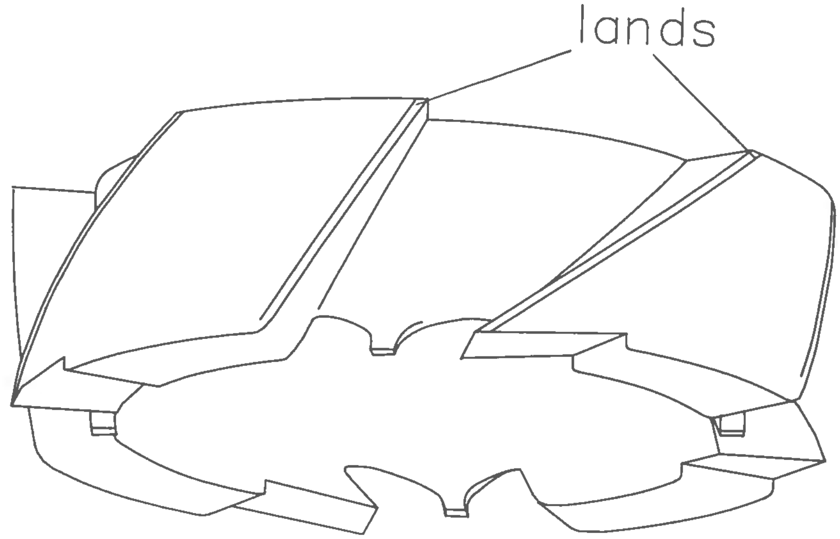
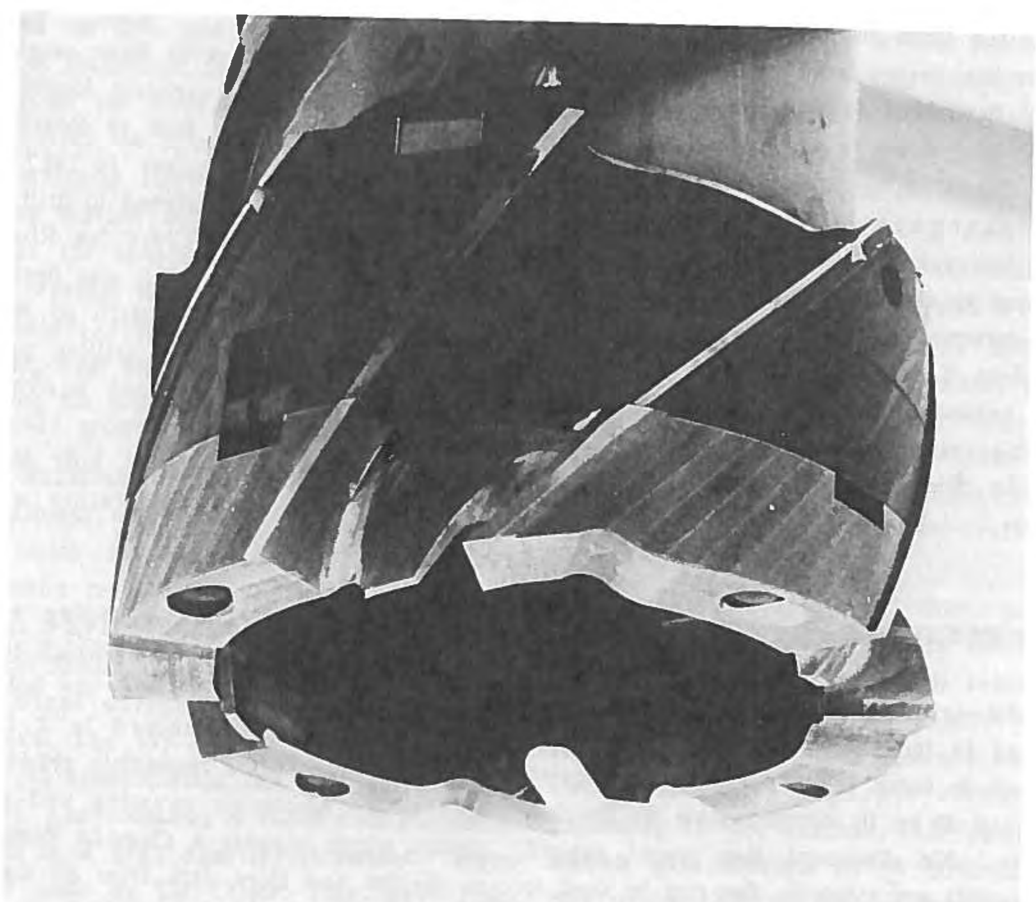


Fig. 2 - The new drill head. It is assembled of three rings (not shown). The cutters are integrated in the lowest ring. The core catchers are fixed to the central part and the upper ring is attached to the core barrel.



ICE DRILLING INSTRUMENTATION

by

Walter H. Hancock and Bruce Koci
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0640, U.S.A.

ABSTRACT

Two types of instrument packages for monitoring the ice drilling process have been designed. Both are mounted in the drill and return information to the surface while drilling. One was used on a hot water during the November-December 1987 summer season in Antarctica. It was powered and controlled from the surface with the data conversion being done using a commercial board in a Compaq computer. The other design was tested in Greenland during June, 1988. It is battery powered and the data conversion is done by a custom microprocessor and electronics package mounted in an ice coring drill. The data is then returned to the surface serially over two data lines. The designs and types of data collected are discussed as well as possible future extensions of the design to include controlling some of the drilling process.

INTRODUCTION

As the depth of the holes that we are drilling in ice increases, it becomes more difficult to sense the condition and progress of the drill by its current draw or the feel of the cable. Compact, low power, rugged components are available that can be used to build sensor and control packages to fit inside the drill. These will allow a better understanding of the way the drill works so that improvements can be made. They will also allow more control so that drill operation can be made simpler and can be optimized for faster drilling.

HOT WATER DRILL

Previously, hot water drills have usually not been instrumented. A separate logging tool was lowered down the hole to measure the results of the drilling process. In 1987, a hot water drill was being designed to drill a 500 meter deep hole in the Crary Ice Rise (1,2) on the Ross Ice Shelf and it was decided to install sensors inside the drill to monitor various parameters of the drilling process. We designed an instrument package to monitor and record the following variables : depth, inclination in two axes, hole diameter, pressure, and water temperature at four points in the system.

The depth is obtained by having a shaft encoder connected to a wheel which rolls on the hose as it is lowered into the hole. The shaft encoder is connected to a Durant totalizing counter for immediate readout and also to an electronic counting and scaling circuit which triggers a Compaq Portable II to digitize and store data from all the other sensors. The other sensors, which are in the drill, are connected to the surface, electronics interface and power supplies through wires are built into the hose. The hose was custom designed (3) and built for this project and has 34 wires built into it.

The inclination was monitored with two Schaevitz (4) model LSFPA inclinometers with a range of plus or minus 15 degrees. The hole diameter was measured by a Schaevitz Type 3000 HCD Linear Variable Differential Transformer (LVDT) type displacement sensor coupled to calipers mounted on the outside of the drill. The calipers are made of stainless steel strips which are bent into an arch shape. One end of the arch is fastened rigidly to the body of the drill, the other end is fastened to a ring which is free to slide along the surface of the drill. This sliding ring is coupled through a push rod to the sensing element of the LVDT. There are three of these arched metal strips spaced at 120 degree intervals around the drill, and the highest part of the arch is in contact with the wall of the hole. Thus as the hole diameter decreases it compresses the calipers, this radial motion is mechanically converted into a very nearly linear motion of the sliding ring, which moves the sensing element in the LVDT. This system allows measurement of hole diameters from 15CM to approximately 45CM, and has the additional function of holding the drill in the center of the hole.

The inclinometers and LVDT are located in a stainless steel container which fits in a slot inside the drill. Power for these sensors is locally regulated to the required plus and minus 15VDC by Zener diodes, with the current limiting provided by the resistance of the wires carrying the power from the surface. The top of this container is left open to accommodate the push rod for the LVDT. The container is filled with Fluorinert which is a high density, electrically inert liquid made by 3M CORP. This heavy fluid stops water from entering the container and provides insulation for the electrical components. A pressure transducer (Omega Model PX440) (5) is included in the container to monitor the height of the column of water in the hole above the drill. This provides a check on the level of water in the recirculating reservoir and also indicates if water is being lost to hidden crevasses. This open container leaves the sensors exposed to the full pressure of the water column. This caused almost immediate failure of the pressure transducer and one of the inclinometers during the antarctic drilling. The other inclinometer and the LVDT worked without problems to the full 500 meter depth.

Four (Omega type 44032) thermistors are located at various places to monitor the change in water temperature as it circulates through the system. The inlet water temperature is measured at the rotating joint where the heated water is first fed into the hose of the winch. The output water temperature is measured inside the drill before it is expelled and after it has traveled through the 600 meters of hose. The discharge water temperature is measured on the outside of the nozzle of the drill water after it has contacted the ice and is starting to mix with the water in the hole. The caliper temperature sensor is located about 3 meters above the nozzle on one of the calipers. The flow rate of the water in the 2.5CM insulated hose was about 75 liters per minute.

Eighteen wires are used, thus, with the exception of the three sensors sharing the +15/-15VDC power supply, all sensors are current loop types and individually powered from the surface. All sensors, without exception, have separate signal lines returning to the surface. All power and signals pass through an 18 conductor slip ring mounted on the axis of the winch, and then to a display panel box. Underneath the display panel are the power supplies and circuitry for buffering, amplifying, and scaling the signals before they are sent to the display meters and computer. All signals are scaled to conform to the +5/-5 volt input range of the A/D board in the computer. Taut-Band analog meters with custom printed scales from Pacific Indicator are used on the display panel.

A Compaq Portable II computer with a Metrabyte Dash-16 data acquisition board installed is used to collect and store the data. A software package, written at Massachusetts Institute of Technology, called Unkelscope is used to control the data acquisition board, display the raw data in graphical form in real time, and store the data for future use. At a later time, the raw data is exported into the Lotus spreadsheet program for conversion from voltage readings into engineering units. Thus a permanent record of the drilling process can be created for future reference.

CIRCUIT DESCRIPTION

The shaft encoder has a 0.3 meter circumference wheel that rides on the hose and puts out 30 pulses per revolution. There are two outputs that are in quadrature so that directional information can be obtained. Comparators are used to convert these 15 volt pulses into TTL compatible 5 volt pulses (Figure 1). A 7474 integrated circuit is used to determine the direction of rotation and direct the count to either the antibacklash circuit or to the scaling circuit. The scaling circuit divides the count by 25 using two 7490 integrated circuits and then a 74123 shapes the pulse to the requirements of the Metrabyte board in the computer. This causes the computer to do an A/D conversion on the other 8 signals every 1/4 meter. The antibacklash circuit consisting of 3-74193's, 3-7485's, a 7408 and a 7404, allows the drill direction to be reversed for a short distance and then advanced again with the data logging resuming where it had left off before the reversal occurred. A switch on the output of the 7474 allows manual selection of the direction of travel during which the data will be logged and allows the operation of the antibacklash circuit in either direction.

Precision reference voltages are required at various places in the circuitry. They are all derived from a Motorola MC1403A 2.5 volt low drift reference I.C. (Figure 2). Power being provided to the sensors in the drill cause voltage drops in the 600 meter long wires which connect them to the circuitry on the surface. This potential signal error source is overcome by using a separate ground sense line and buffering it and the signal lines with high impedance low drift amplifiers. This method is used on the LVDT and Inclinometers which produce voltage outputs (Figure 3). The analog display meters used for these signals use a +/- 5 volt center zero meter movement with custom scales.

The pressure sensor (Omega PX440) has a 4-20ma current loop output, thus the resistance of the wires is unimportant except in the determination of the power supply voltage (Figure 4). In this case, the 110 ohm resistance of the wire dictated a 35 volt supply for this sensor. A 500 ohm resistor is used as a current to voltage converter and this signal is buffered by a low drift amplifier before it is applied to a 10 volt left zero meter with a custom scale printed to show zero PSI with a 2 volt input and 1000 PSI with a 10 volt input. The 2 to 10 volt signal is amplified and offset to provide a +/- 5 volt signal to the computer.

The 4 temperature sensors are thermistors which vary their resistance as a function of

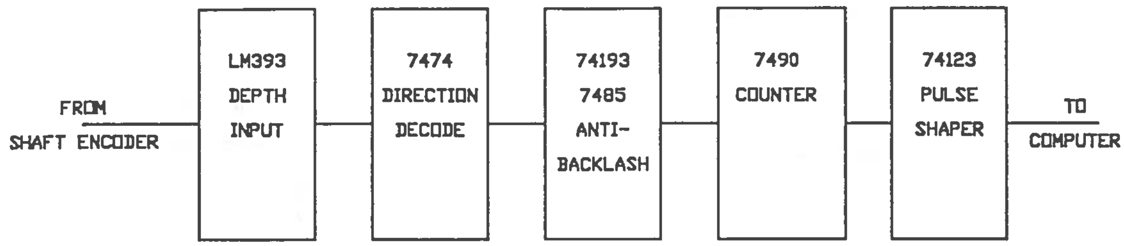


FIGURE 1. BLOCK DIAGRAM OF DEPTH RECORDING CIRCUIT.

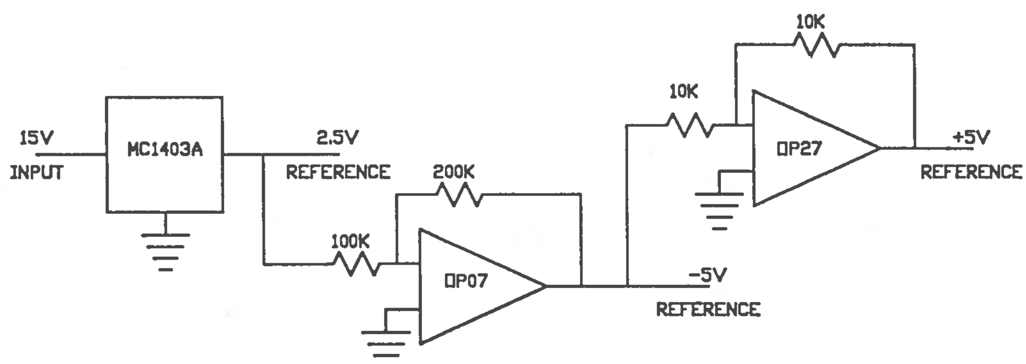


FIGURE 2. DIAGRAM OF VOLTAGE REFERENCE CIRCUIT.

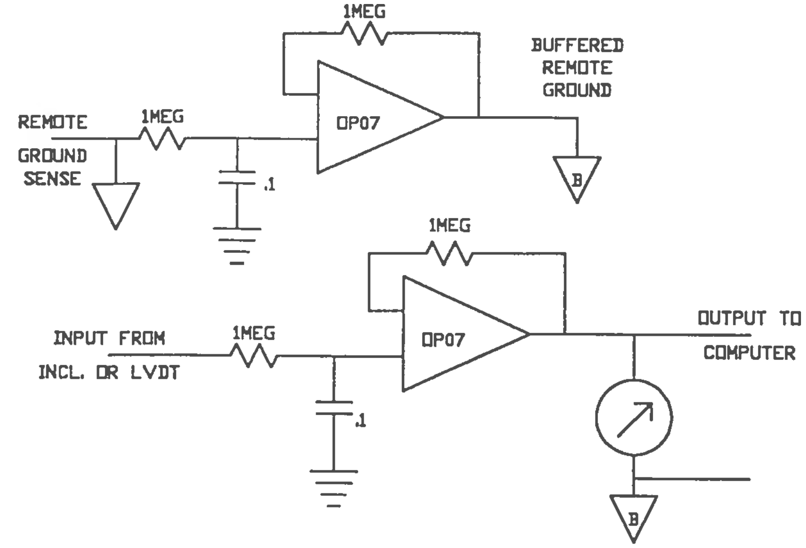


FIGURE 3. CIRCUIT DIAGRAM FOR SENSING REMOTE SIGNALS.

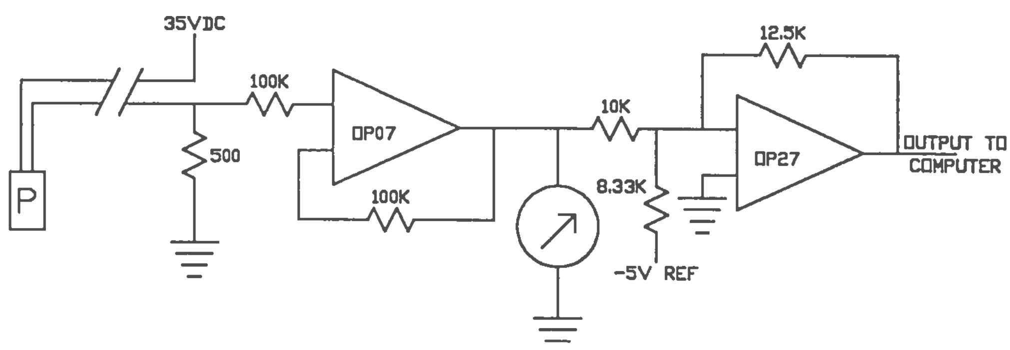


FIGURE 4. PRESSURE SENSING CIRCUIT.

temperature, thus the resistance of the connecting wires must be included in the calculations. A fixed voltage is applied to the thermistor (Figure 5) and the current that flows through it is converted to a voltage, and simultaneously offset to provide the +/- 5 volt signal needed by the A/D board in the computer. A high value thermistor (30k @ 25 degrees centigrade) was chosen to minimize the effect of the wire resistance. The output of this circuit is nonlinear and inverted, thus the 10 volt left zero meter has a custom nonlinear scale printed to show -40 degrees with a 0 volt input and +100 degrees centigrade with a 10 volt input. The temperature is calculated in the computer by using an equation which recovers the resistance of the thermistor from the input voltage and then using a lookup table derived from the calibration curve for the thermistor.

ICE CORING DRILL

An ice coring drill has been designed at PICO to be used in Greenland to drill a deep fluid-filled hole (6). In contrast to the large number of wires available in the hose for the hot water drill just described, only 7 wires are available in the cable for the ice coring drill. This limited number is due to manufacturing considerations and also due to the great length of the cable. More wires in the 1165 meter Kevlar reinforced cable would add a great deal of weight and bulk to the cable and to the winch used to carry it. To transmit a large amount of power to the drill over the small wires available in the cable, we transform the 240VAC input to 480VAC at the surface. Four of the available wires are used to carry the high voltage AC power to the drill where it is transformed down to 120VAC and converted to DC current for the drill motor. This leaves only three wires to carry control signals between the drill and the surface. An instrument package has been designed to go into the ice coring drill to monitor various parameters in the drill and to transmit that information back to the surface for display and storage. The instrument package in the drill also receives commands from the surface to control the direction of the drill motor as well as some other aspects of the package operation. Due to the large number of parameters to be monitored and the high speed communications needed for control the instrument package is designed around a high speed microcontroller with a built in serial I/O port. The electronics circuitry that goes in the drill is contained in an aluminum pressure vessel that is sealed with O.Rings and has high pressure electrical feedthroughs. This pressure vessel is the same diameter as the rest of the drill and forms a structural member of the drill assembly. The electronics circuitry that remains on the surface is mounted on a control panel that fits inside the box containing the power control for the drill motor.

The parameters that are monitored are : depth, inclination in two axes, azimuth, motor RPM, motor voltage, motor current, fluid pressure and temperature in the hole, air pressure and temperature inside the pressure vessel, battery voltage and cable tension. The depth is measured at the surface using a shaft encoder mounted on the axle of the sheave at the top of the drill tower. The pulses from the shaft encoder are in directional quadrature and are counted by a Durant counter/display and also by a microprocessor in the control panel. All the other signals are measured by the electronic circuitry in the drill.

The microprocessor in the drill controls a 16 channel 12 bit data acquisition subsystem (Model AD364SD) manufactured by Analog Devices (7). It also controls four relays which have the following functions : battery charging relay, drill reversing relay, drill stop relay and sensor power relay. The microprocessor is an 87C51 manufactured by Intel (8). It is programmed to wait for a control command from the control panel at the surface which tells it which relays to turn on/off, when to enable the data acquisition subsystem (DAS) and when to transmit the data to the surface.

The control panel also contains an 87C51 microprocessor. This microprocessor is programmed to monitor the switches located on the control panel and send control commands to the drill in response to switch changes. It also counts pulses from the shaft encoder to monitor drill depth. It receives the raw data from the drill and stores it temporarily for display on the control panel. The bulk of the program in the control microprocessor does an immediate conversion of the raw data into actual numbers for display on the control panel. When the sensor power switch on the control panel is on, new data is acquired, converted and displayed three times each second. When data logging is enabled by a switch on the control panel, data to be permanently stored is sent to Compaq Portable II computer every 20 cm of change in drill depth. Communication with the Compaq computer is via it's standard serial interface port and the data is stored in a Lotus spreadsheet by a communications program called Lotus Measure.

CIRCUIT DESCRIPTION

The electronics circuitry in the drill is designed around an Intel 87C51 microcontroller (Figure 6). This is a complete microcomputer on a chip. It has built in EPROM program memory, RAM data memory, CPU, I/O ports, and serial communication port. The 87C51 in the drill communicates with the control panel at the surface, executing commands sent to it and returning data to the surface. These commands determine the status of the four relays and of the data acquisition process (Figure 7). The stop relay is used to disconnect AC power from the AC to DC converter and thus remove power from the drill motor. This allows the reversing relay to reverse the polarity of the DC current to the motor without excessive arcing. The battery charge relay is used to connect the battery to the DC motor voltage through a resistor so the battery can be partially recharged while the drill is running. A 12 volt gell cell type lead acid battery is used to provide power for the electronics package in the drill due to the limited number of conductors available in the drill cable. The components in the electronics package were chosen both for cold temperature operating ranges and for low power operation to minimize battery drain. The sensor power relay (Figure 6) allows the package to be put in a very low power standby mode by disconnecting the data acquisition system and sensors from the battery. In this standby mode, the 87C51 and DS3696 driver chip together only draw about 50MA, but are still fully active and can still control the relays. An even lower mode is possible, but has not been implemented, whereby the 87C51 itself can be put in a standby mode. When the DAS is enabled, it and the sensors draw about 500 MA from the 12V battery. The battery has a 12 amp hour rating and thus could carry this load for a number of hours depending on temperature. Most of the 500MA is used by the (Calex Model 12D15.100) 12V to +/- 15V converter which supplies the voltages required by the sensors ans DAS.

The AD364 DAS consists of two chips, an AD574 12 bit 35 microsecond analog to digital converter and an AD362 sample and hold and 16 channel multiplexer. The 87C51 controls both of these chips using one its I/O ports and receives data from the A/D

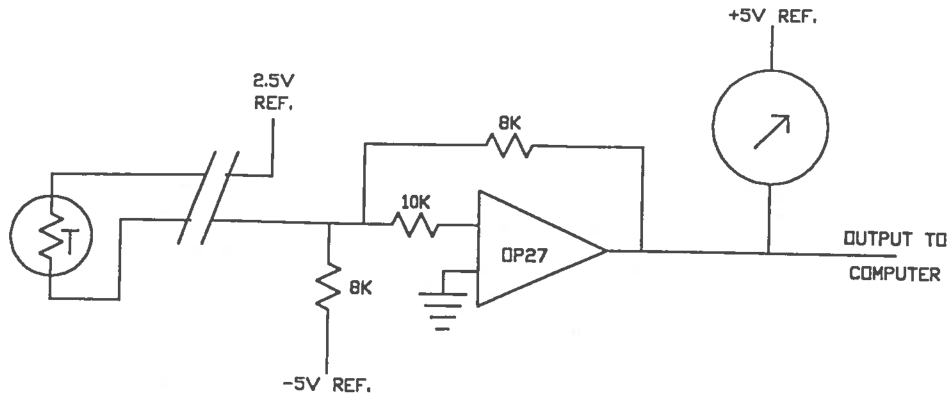


FIGURE 5. TEMPERATURE SENSING CIRCUIT

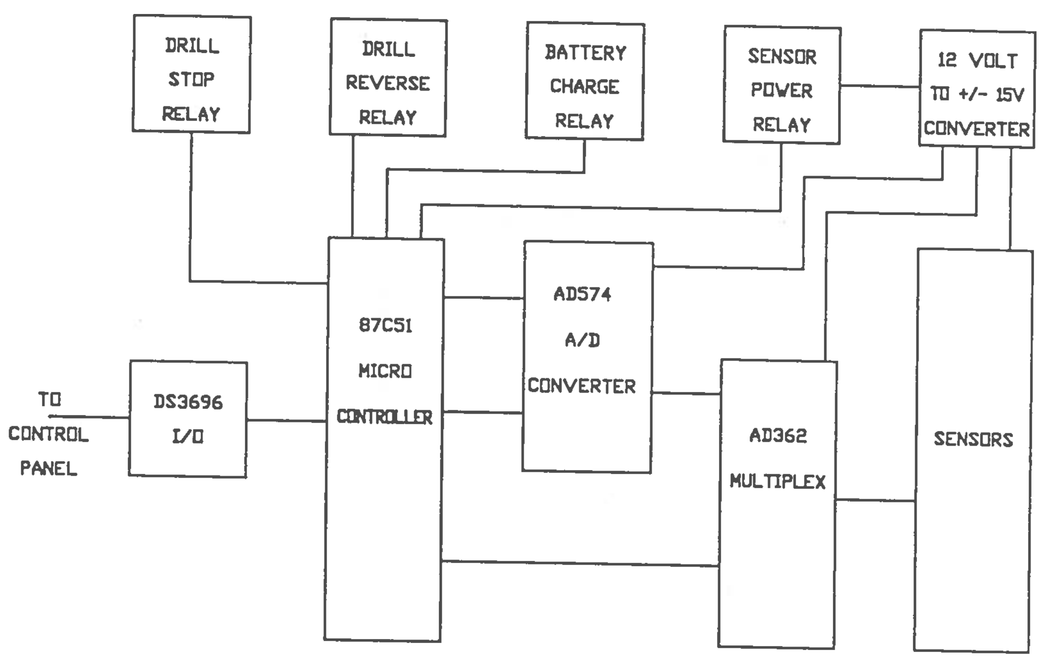


FIGURE 6. BLOCK DIAGRAM OF CIRCUIT IN ICE CORING DRILL

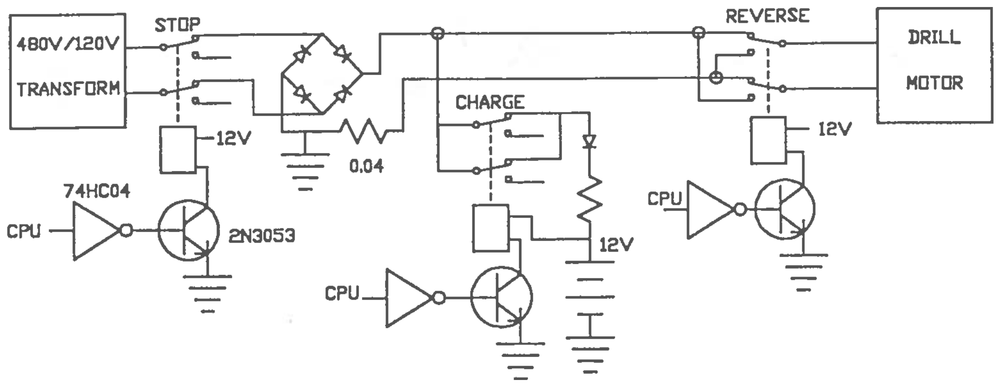


FIGURE 7. DIAGRAM OF HIGH POWER CIRCUIT IN DRILL

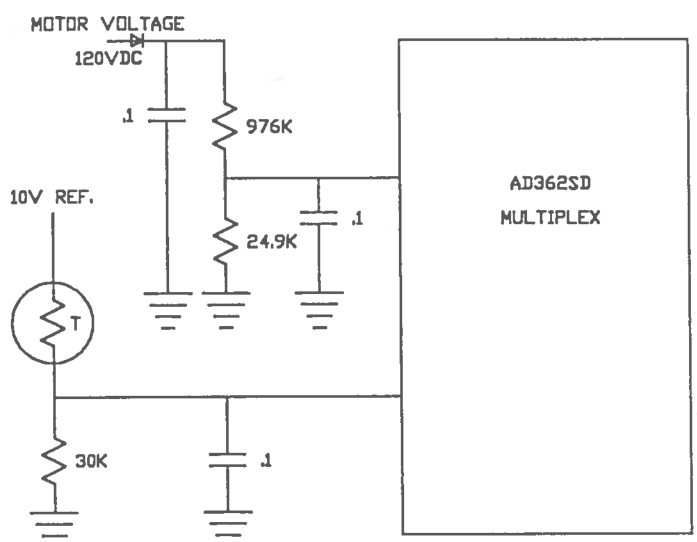


FIGURE 8. EXAMPLE OF SIMPLE CONDITIONING REQUIRED FOR SIGNALS

converter through another of its I/O ports. The 87C51 causes the multiplexer to step through the 16 signals that are available and present them one at a time to the A/D converter. The A/D converter then converts the signal to a digital value which is stored in the 87C51 until all channels have been converted. The data is then transmitted to the control panel at the surface.

The inclination is measured by two Schaevitz (part 2338-03) inclinometers which have an output of 60 MV per degree of tilt. A Watson (9) (Model FGM200A) three axis fluxgate magnetometer is used to provide both a cross check on the inclinometers and an azimuth indication. The output of each magnetometer axis is 1 volt per 250 milligauss. The motor current is measured by placing a .04 ohm resistor in the motor power wiring and measuring the voltage across it. This provides a signal of 1V/25AMPS. The six signals just described require no buffering or scaling. They are usable directly by the +/- 5 volt input range of the A/D converter. Having the DAS close to the signal sources eliminates the problem of voltage drops and noise in long signal lines. Also, by having a digital readout on the control panel, all the scaling and level shifting is done by the microprocessor thus eliminating a lot of analog circuitry such as that used in the hot water drill display panel shown earlier.

Omega pressure transducers (type PX176) are used to monitor the fluid pressure in the bore hole and the air pressure in the sealed cylinder that contains the instrument package. These transducers have an output range of 1V to 6V and thus a simple resistive voltage divider is used to bring the signal within the input range of the A/D converter. The air pressure in the cylinder is monitored to determine if fluid is leaking into the cylinder under the high pressures expected in the bore hole. Other signals that need resistive dividers to bring them within the correct A/D input range are motor rpm, motor voltage, battery voltage and the 10V system reference. The motor rpm signal produced by a tachometer in the motor is 10V/1000RPM and can be as high as 50 volts. Motor voltage can be as high as 120VDC. Temperature measurement is much simpler with a microprocessor because the nonlinear resistance verses temperature curve of the thermistor can be corrected in software. Thus, the simple resistor circuit shown in Figure 8 along with a calibration curve in memory is all that is required to obtain a temperature signal. The thermistor used is an Omega type 44032.

The tension in the cable (minus the weight of the cable) is measured by a load cell which is mounted so that it provides the connecting link between the cable and the drill. The information provided by this sensor indicates the weight on the cutters while drilling, the tension required to break the core, the drag of the antitorque skates on the hole wall as the drill is being retrieved and the weight of the core and chips being returned to the surface. The load cell used (Omega Model LCC) has no internal signal conditioning circuitry, so the circuit in Figure 9 provides this function. The 10V at 22MA required to power the load cell resistor network is beyond the capability of the precision opamp used to produce the system 10V reference. By adding the 223 ohm resistor from the + 15V supply, the 22MA current requirement is met, thus the system reference only has to provide very small correction currents to maintain the precision 10V input required by the load cell. The output of the load cell is only 30 millivolts for a 5000LB load, thus a great deal of amplification is required to provide a usable signal. The Analog Devices AD625B instrumentation amplifier circuit provides a gain of 417 which gives a signal of 1V/400LB.

The electronics circuitry in the control panel is also designed around the 87C51 microcontroller (Figure 10). The signals from the shaft encoder are filtered and level shifted by the LM393 comparators and then go directly into an interrupt input on the 87C51. An interrupt service routine then determines the direction the cable is moving and updates the depth count in memory. A Durant counter provides a backup count and display, but, since the sheave is not the same circumference as the wheel the shaft encoder was designed for, the readout provides a number proportional to depth rather than the actual depth. The 87C51 can be reprogrammed for any wheel diameter so that the readout it provides is the actual depth in meters. The two CD4532's and a CD4071 encode 16 switches into 4 input port pins of the 87C51. Another 6 switches are attached to 6 other input port pins. The microprocessor interprets the switch setting and based on these settings either sends commands to the drill, displays requested data on the front panel, or sends data to the external computer to be logged. When the readout select switch is turned to the desired signal, the 87C51 retrieves the raw data most recently received from the drill, does a calculation to put the data into readable form, outputs the result to the CD4511 latches which drive the LED displays. It then updates the display it new information is received from the drill or the display select switch is changed. Communication with the drill uses the same bidirectional differential transmission line driver (National Semiconductor DS3696) (10) as is used in the drill. This chip is connected to the 87C51's serial I/O port through a relay controlled by the 87C51. When data is to be logged to the external computer, the relay connects a serial line driver (Maxim MAX232) (11) to the microcontroller's serial I/O port. The control panel circuitry all operates on 5V only, so the MAX232 chip has internal converters and inverters to provide the +/- 12V signal levels required to communicate with the serial port on the external computer.

A program called Lotus Measure controls the serial port on the Compaq II portable computer to accept the data from the control panel and store it in a Lotus 123 spreadsheet. The data sent to the computer is the same raw data that the control panel had received from the drill. This allows higher precision calculations to be performed on the data than were possible in the microcontroller due to program size limitations.

CONCLUSION

The two instrument packages described in this paper are first generation designs for PICO and were designed, constructed and used within the past year. The microprocessors in the ice coring drill were capable of doing a great deal more than they were asked to do in this design. We plan to do more work on closing the control loop for a number of drilling processes. For example, the microprocessor could monitor the azimuth for spin caused by slippage of the antitorque system, then stop the drill and either notify personnel on the surface or automatically correct the problem itself. The repetitive tasks of raising the drill to the surface to retrieve the core and then lowering it again could be automatically controlled. The drill motor speed could be controlled in the drill with only a digital command from the surface to specify a speed to maintain. High speed data acquisition and communication allows much better visual indicators to be available to the

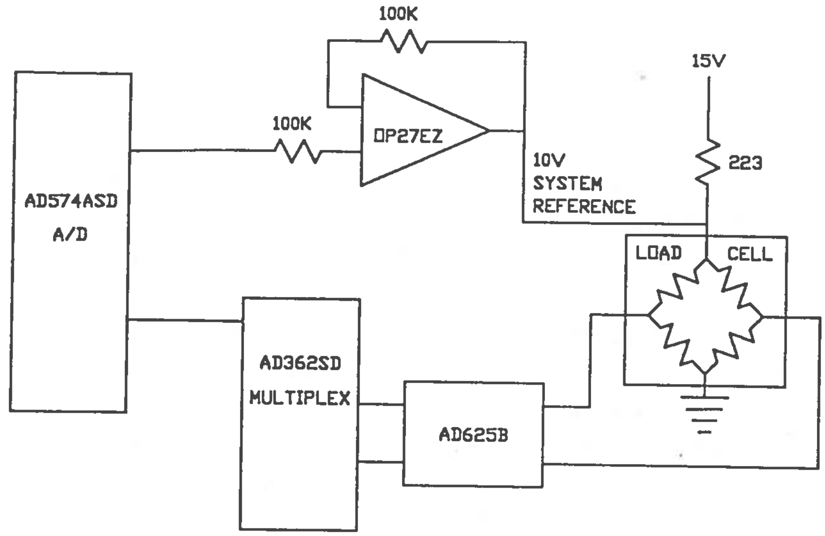


FIGURE 9. DIAGRAM OF LOADCELL CIRCUIT

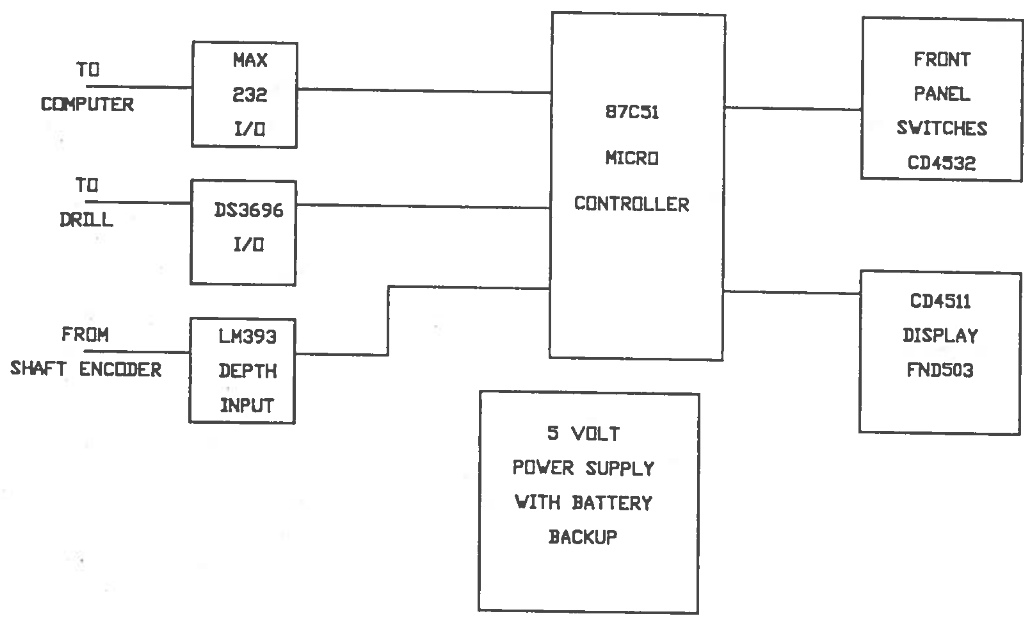


FIGURE 10. BLOCK DIAGRAM OF CONTROL PANEL CIRCUIT

personnel on the surface. The extremely long cables now coming into use seem to act like springs when a heavy drill is on the end of them. This makes it almost impossible to precisely control drill bit pressure and drilling rate by pulling or pushing on the other end of the spring. A jack screw mechanism could be installed in the drill itself along with force and displacement sensors which would allow a microprocessor in the drill to precisely control the drilling process locally. This could provide for a smoother penetration rate for higher core quality.

We are exploring the possibility of using a fibreoptic cable as a higher speed communication link in the drill cable. This would eliminate electrical interference problems between the power conductors in the cable and the communication conductors in the same cable.

In conclusion, it seems that we are just beginning to scratch the surface in applying new electronics technologies to improve the art of ice core drilling.

ACKNOWLEDGEMENTS

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HOLE LIQUIDS

by

N.S. Gundestrup
Geophysical Institute
Haraldsgade 6
DK-2200 Copenhagen N
Denmark

In deep drilling, the hole must be filled with a liquid in order to prevent hole closure from the surrounding ice. The maximum depth received in a dry hole is 906 m at Dome C using a thermal drill in ice with a temperature of -50°C (Ritz and others, 1982). In Greenland, a thermal auger reached 404 m in -30°C ice (Clausen and others, 1988). Mechanical drills have a more limited depth capability in a dry hole than a thermal drill due to the lack of clearance at the drill head. Nevertheless, it was possible to core 360 m at South Pole (-55°C) and 325 m at Renland in East Greenland (-18°C). In deeper drillings, the hole has to be filled with a liquid.

The ideal hole liquid has a density of 920 kg/m^3, does not react with the ice hole wall, is completely miscible with Jet A1 (Kerosene) that serve as the main hole filler, is cheap, has a low viscosity and not toxic. In practice, severe compromise has to be made as the following indicates :

At Camp Century (1966) and Byrd Station (1968) the main filler was DFA (Hansen, 1976). The chips produced while drilling were dissolved by a glycol/water mixture and the major part of this mixture brought to the surface in a bailer in the drill. The density was increased from the 825 kg/m^3 of pure DFA to 920 kg/m^3 by adding trichlorethylene. This four-component liquid (DFA/-trichlor/glycol/water) worked fine as evidenced by the recent logging of the Byrd hole (Hansen and others, in prep.). 20 years after completion of the drilling, the hole is open. The mixing ratio of glycol and water is critical in order to prevent slush to be formed : Slush formed due to the use of excessive amounts of glycol used to compensate lack of trichlorethylene lead to the loss of the drill in 1969. The main drawback was the use of trichlor, that is quite poisonous. While drilling, the operators has to inhale the fumes on sustain spray of liquid.

In the russian drillings in Antarctica, alcohol/water has been used, both to dissolve ice and as hole liquid. The mixture is clean, has relatively low viscosity and is not toxic. It has served well in spite the absence of a stable alcohol/water ratio. The last means, that the hole will be destroyed with time. The mixture has mainly been used at places with an ice temperature of -50°C, and at these temperatures the hole wall dissolves so slowly, that the hole has been usable for several years. Morev and Yakovlev (1984) has provided graphs on mixing ratio, density and viscosity versus temperature. In other drillings, pure hydrocarbon (DFA?) has been used although little information is available (Kudryashov and others, 1984). Again, due to the low temperatures, the hole has been usable for several years in spite of the hole liquid density of around 860 kg/m^3.

In the US/Danish/Swiss drilling at Dye 3, South Greenland, the main filler was Jet Al with perchlorethylene as densifier (Gundestrup and others, 1984). Again, perchlor is unsafe to work with.

The Australian deep drilling at Law Dome, Antarctica, will use Jet Al as main filler and has considered Freon 11 (CCl_3F, Trichlorofluoromethane) as densifier (Vin Morgan, private communication). Freon 11 is completely miscible with Jet Al, non-flammable, low viscosity, chemical inactive and not as toxic as perchlor or trichlor. Density is 1579 kg/m^3 at -20°C. It seems as an ideal densifier except for its possible role in the creation of the ozone hole. Until Freon 11 is found not to participate in the destruction of the ozone layer, this may preclude its wider acceptance as densifier. Freon 113, having a higher boiling point and sligthly less harmfull effects on the ozone layer may be a better choice than Freon 11.

DENSITY REQUIREMENT

As it is difficult to find an ideal hole liquid, the allowable range of liquid densities should be considered. Johnsen and others (1980) has calculated the hole closure rate at different temperatures and pressure differential. Based on this figure, we obtain the following table of closure rates in mm/yr of a 100 mm hole :

Table 1 - Closure rate in mm/yr

pressure differential	0	-10	-20	-30	-40
5 bars	11	2.6	.6	.15	.026
10 bars	75	18	4.5	0.9	0.15
20 bars		170	37	7.3	1.4

The table shows the significant changes in deformation rate with temperature and pressure. At ice temperatures belows -40°C, a pressure differential of 10 bars causes insignificant deformation ratio. In deep drilling however, the bottom temperature approaches 0°C, and thus the pressure should be correct within a few bars : In a 3000 m deep hole, the bottom pressure is 270 bars. If we want the pressure to be correct within 3 bars, the maximum density error is ± 9 kg/m^3.

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ELECTROMECHANICAL ICE CORE DRILLING SYSTEMS : A DISCUSSION

by

K.C. Kuivinen and J.M. Sonderup
Polar Ice Coring Office
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0640, U.S.A.

INTRODUCTION

The following is a summary of comments presented during an open discussion on electromechanical ice core drilling systems at the Workshop on Ice Core Drilling in Grenoble, France on October 10, 1988.

Comments regarding the characteristics of existing ice core drilling systems are attributed to the respective laboratory or institution by the following abbreviations : AWI - Alfred Wegener Institute, Federal Republic of Germany ; ILTS - Institute of Low Temperature Studies, University of Hokkaido, Japan ; PICO - Polar Ice Coring Office, University of Nebraska-Lincoln, U.S.A. ; UBern - Physics Institute, University of Bern, Switzerland ; UCPH - Geophysical Institute, University of Copenhagen, Denmark.

The discussion of electromechanical ice core drilling systems proceeded with the identification of major drill components and the various approaches, design criteria, fabrication techniques, and field experiences related to each component.

DRILL HEAD

Cutters.
The cutting angle should be 45 degrees with a 15 degree relief angle. There should be a relief angle on the I.D., none on the O.D. UBern has tested a precutter on the I.D. which cuts a 1.5 mm etch on the core prior to cutting with the main cutters. Coarse chips should be produced by the main cutters, of which there are usually three or more. The cutter shapes recommended for use after pore close-off are : flat cutters with an inside radius (UCPH), double-angle cutters (PICO), round cutters (AWI).

Penetration Shoes.
It was generally agreed that penetration shoes are indispensable. Shoes should be used to control the patch angle which is recommended at 1.2 degrees normally, 1.3 degrees in warm ice, and 1.1 degrees in really cold ice.

Core Catchers.
Core catchers, also known as core dogs, should be positioned as low as possible in the head. They should have the same cutting

angle as the cutters (30-45 degrees), and must be kept very sharp to achieve the best core-break. Springs should be used to keep the core dogs upright during drilling. Core dog mechanisms should be kept free of ice and snow chips. Alternative core-break techniques (e.g., sawing) should be investigated to enhance core quality at the break.

Rotation Speed.
The following recommendations were made : 1.2 revolutions per second or 100 rpm (UCPH, PICO), 50-150 rpm (UBern), although rotation speed may vary with the chip removal system selected.

Brittle Zone.
The ultimate goal is to drill to the brittle zone in an open hole while collecting good quality core.

BARRELS

Outer Barrel.
The clearance between the O.D. of the outer barrel and the borehole wall is recommended at : 1 mm (UCPH), 2 mm (PICO), 3 mm (ILTS). The outer barrel specifications vary as follows : 2 mm wall thickness with three ribs 2 mm thick attached to the inside of the barrel (PICO), 2 mm wall with five ribs 1.5 mm thick (UBern), 1.6 mm wall with ribs 0.7 mm thick (ILTS), while UCPH uses a 2 mm wall with a series of grooves 1 mm deep in order to conserve space.

Inner Barrel.
All participants use spiral flights attached to the O.D. of the inner barrel to move chips upward from the cutting head to the chip storage chamber. High-density polyethylene is the preferred material for the flights. The recommended pitch of the flights is : 180 mm per revolution for 78 mm core diameter (UCPH), or 45 degrees (PICO). Recommendations for the number of flights include : should match the number of cutters for the first 20 cm above the bits (PICO), and four flights for the first 15 cm, then two flights along the entire legth of the barrel (UBern). Flight thickness is recommended at : 3 mm (ILTS), 8 mm (PICO), 6.5 mm (UCPH). Clearance between the I.D. of the inner barrel and core is suggested at : 0.5 mm (AWI), 1 mm (UCPH), 1.5 mm (PICO), 2.5 mm (ILTS). All inner barrels should include some sort of suspended (not free floating) device to separate the stored chips from the ice core ; UBern, PICO and UCPH use a polyethylene disk or "little men" suspended by a string from one of the inner barrel chip ports. The I.D. of the inner barrel should be very smooth so the core is not affected by the barrel rotation.

Barrel Materials and Specifications.
The inner barrel should not be more out of round than one-half the clearance between the core and inner barrel wall : the greater the clearance, the more out of round the tubing can be. PICO requires a concentricity of < 0.1 mm and a straightness of 0.04 inch per 12 feet. Acceptable tubing can be gotten by personally selecting tubing from the manufacturer or vendor (UCPH, UBern), or by specifying custom tubing from a manufacturer such as Kaiser Rollmet (PICO). Irregularities between inner and outer barrel can be overcome by machining the flights so that the inner barrel rotates freely inside the outer barrel. While most barrels used today are steel, composite barrels should be experimented with since they can be made more round and straight than steel tubing, flights can be wound as an integral part of the barrel, and the inside of the barrel can be slightly tapered to allow easier core removal.

TORQUE RESTRAINT AND DETECTION ; SLIPRING

Anti-torque Mechanism.
A variety of anti-torque mechanisms have been used. UCPH uses three leaf springs clamped at both ends with a very sharp edge on the corner of the flat blade surface (see N. Reeh contribution in the Calgary Ice Drilling Technology Workshop volume). PICO uses three leaf springs clamped at both ends with the springs angled outward so the edge cuts into the hole wall. AWI uses three blades in the original design by H. Rufli. UBern's latest design uses rollers on the blades (or skates) which may protect the hole wall better in firn. ILTS cuts grooves in the hole wall.

Hammer.
Participants generally agreed that a hammer built into the drill as high as possible was a good idea. The deeper one drills, the more one is needed to break core and free a stuck drill. It was recommended that the hammer should weight a minimum of 10 percent of the total drill weigh and have about 10 cm of travel.

Rotation Detection.
Some device for detecting drill rotation is a good idea in both routine and test situations.

Slipring.
The slipring assembly preferred by UCPH is a simple version inside the drill hammer. PICO, UBern and AWI buy more expensive but excellent commercial sliprings from IEC Corporation.

Drill Recovery.
To ease recovery of a lost drill that breaks free of the cable, add a hook to the top of the drill for better grabbing by a fishing tool.

CABLE

There is a choice of cables, both in terms of electrical conductors, strength, durability, weight and armor material. The two primary choices are steel or kevlar reinforced cables, both of which can be bought with shielded conductors for the 300-400 m depth applications. Steel has the advantages of being stiffer, more durable and longer lasting, with the disadvantage of being heavier. Kevlar has the advantages of being lightweight with the possibility of including fiber optics ; and the disadvantage of being more elastic than steel. Cables seem to be a matter of personal preference.

TOWER AND WINCH

Tower.
There are essentially three tower options available : the vertical mast, a tilting tower or a horizontal tower. PICO uses a single round fiberglass mast 15 m tall, assembled in sections of tubing joined by aluminium couplers and guyed in place. The mast is 10-15 m tall, and is not stiff enough for a long drill. UBern uses a triangular ladder mast assembly which permits one to climb up the mast. AWI uses a single tubular mast. UCPH uses a tilting tower mounted on a sled. This short tower causes some problems with self-spooling of the cable on the winch.

Winch Base.
The winch base should be kept stable and level during drilling.

CONCLUSION

Each participant offered specifications of components and field experiences with new and existing components.

THERMAL ICE CORE DRILLING

THERMAL ICE CORE DRILL 4000

by

Augustin L., Donnou D., Rado C., Manouvrier A., Girard C., Ricou G.
Laboratoire de Glaciologie et Géophysique de l'Environnement du C.N.R.S.
St-Martin d'Hères, France

INTRODUCTION

The "Laboratoire de Glaciologie et Géophysique de l'Environnement" has developed since 1968 a thermal drill system, which reached 905 meters in depth during the summer season 1977-78 at Dome C (Antarctica).

In order to reach deeper layers, we had to modify the system for working in a fluid filled hole.

In 1981-82 in Adelie Land two sets of equipment for drilling in a fluid filled hole were tested (1). The results encouraged us to build a thermal drill with a 4000 m cable and associated winch.

In 1984 the L.G.G.E. has conceived and built a core drill able to take back 8 metres long ice cores in order to reduce operating time. Its implementation has required the use of composite materials.

DESCRIPTION AND RUNNING

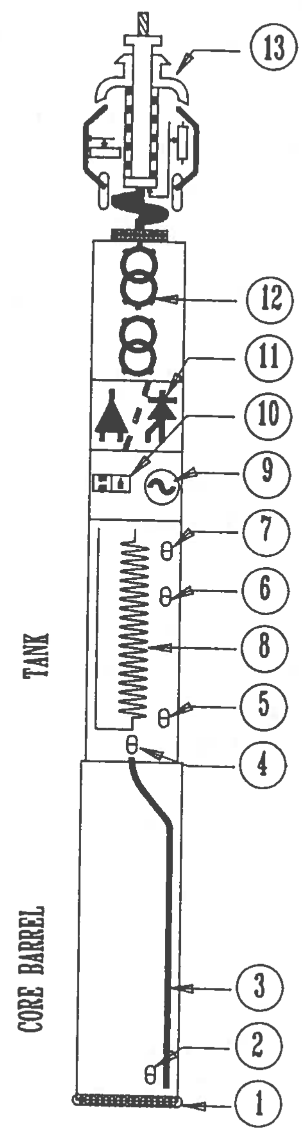

Figure 1 - Schematic diagram of the drill
(1) Bare resistance wire. (2) Temperature sensor : level of water in the hole. (3) Sucking tubes and its heating elements. Temperatures sensors : (4) sucked up water and running of the pump, (5) bottom of the tank, (6) middle of the tank, (7) top of the tank. (8) Tank heating element. (9) Pump. (10) Electrovalve. (11) Electronics. (12) Transformers. (13) Suspension.

The drill head is in contact with the bottom of the hole. The power is applied to the heater element, a bare resistance wire, causing the head to melt an annular space in the ice. The core passes into the core barrel. A temperature sensor is 10 centimeters above the drill head. This sensor gives us the level and the temperature of the water from melting. The melt water goes up in the three sucking tubes and arrives at the bottom of the tank where a temperature sensor gives information about the pump workings.

Three other temperature sensors allow checking of the water level in the tank.

When the temperature at the top of the tank is positive, we have to stop drilling.

Drilling fluid sucked up by the pump is replaced by meltwater in the tank. The electromagnetic pump always sucks drilling fluid, never water.

The electrovalve has two functions :

- It allows an air inlet at the top of the tank to empty it at the surface.

- This air inlet allows the filling up of the tank when the drill goes down.

The electronic section controls each part of the drill. Telemetering and remote control circuits are needed to transmit informations about drill operations from the drill to the control desk.

There are two transformers :

- A triphase one supplies the drill head.

- A single phase transformer supplies the electronic, the electrovalve, the electromagnetic pump, the water tank, the heater and the heater sucking tubes.

The suspension controls the pressure on heating head and also the verticality of the drill. There is also a device to measure hole diameter in this section. The anchoring of the cable is on the top of the suspension.

Except for the electronics, each part of the drill is at the same pressure as the drilling fluid. The total length of this thermal drill is about 22.4 meters.

DRILL HEAD

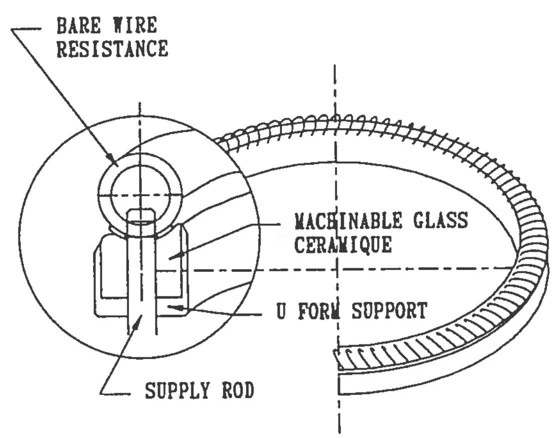

Figure 2 - Drill head

The drill head consists of :

- a spiral bare resistance wire fixed below a machinable glass ceramic insulator.

The resistance wire is made of Kantal. Kantal is a magnetic material, made of 22 % chrome, 5,5 % aluminium and 75 % iron. The Kantal has a good thermal resistance : 1375°C. Its tensile strengh is 750 N/mm^2. The wire diameter is 1,3 mm and its developed length is about 3,8 m. The heating power is 7500 w at 50 Vac.

The resistance is supplied in 3 points by copper rods soldered with silver. The wire resistance is fixed by 3 other rods on the support.

The machinable glass ceramic support is made of six sections and inserted in the stainless steel U form, which protects it from mechanical shocks. Ceramic type is "MACOR". Its mechanical strengths are good. Its thermal resistance is 1000°C continuously.

The drill head is an interchangeable part. This set up allows quick reparations.

PISTON EFFECT

The drill moves like a piston in the fluid filled hole. To reduce the resistance of this effect and increase the speed of the drill in the hole we have found several solutions :

- Only the core barrel has a 145 mm diameter, the other parts of the drill have an outer diameter of 130 mm.

- Four bored holes at the top of the core barrel avoid imprisonment of air bubbles. They allow fluid passage inside the core barrel when the drill goes down.

- Core barrel section shape allows a good fluid passage along the tube in spite of its 145 mm diameter. So the piston effect is located at the drill head.

- Flap valves on the drill head allow fluid passage inside the core barrel when the drill goes up with the ice core.

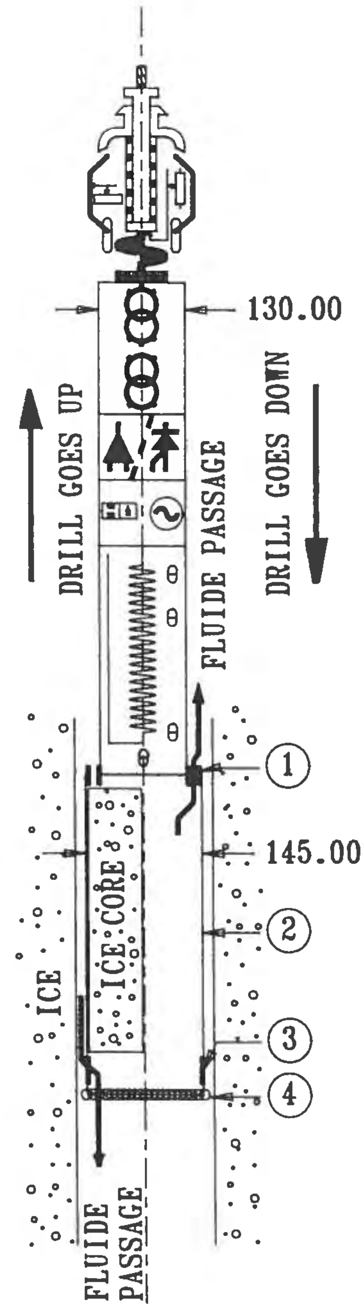

Figure 3 - Piston effect : Left part of the drawing : the drill goes up with the ice core inside the core barrel. Right part of the drawing : the drill goes down. (1) Four boring holes. (2) Core barrel section (see next paragraph). (3) Flap valve. (4) Piston effect zone.

CORE BARREL

The use of composite material is imposed by the length, the thickness and the particular shape of its section.

A combination of kevlar and carbon fibres gives an excellent tensile and compressive strength.

The core barrel was made in this laboratory. It was moulded around an aluminium core held vertically to avoid bending. The core barrel wall has seven fibre layers. First layer : fibreglass is teflon coated on one side. This surface allows easy release of the core barrel from the aluminium and also later for extracting the ice core from the drill. The second layer is made of kevlar fibres (300 gr mm^{-2}). The third is made of carbon fibres (200 gr mm^{-2}). The fourth is made of kevlar fibres again. Fibre-glass tubes are stiked on the fourth layer. They are used to insulate the three power supply rods, the temperature sensor and also used as sucking tubes. Then we find alternately a kevlar layer, a carbon layer and a last kevlar layer coated with white polyurethane.

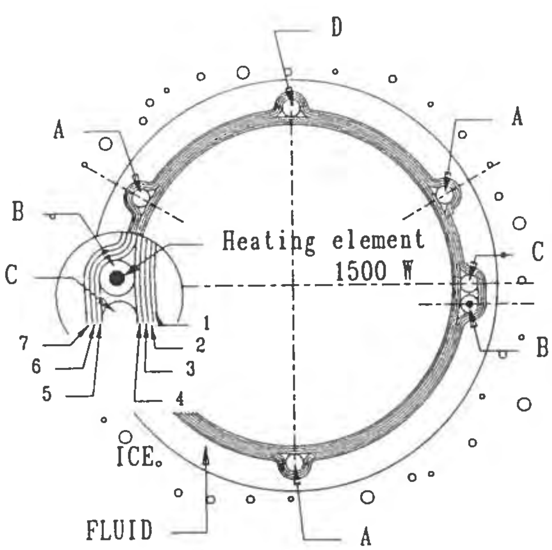

Figure 4 : Core barrel section. (A) Feeding drill head. (B) Sucking tubes. (C) Feeding heating elements of sucking tubes. (D) Tubes for temperature measurement. (1) Fibreglass and teflon. (2) Kevlar. (3) Carbon. (4) Kevlar. (6) Carbon. (7) Kevlar.

The resin used (E.P.O. 20-12 RESOLIN) is a bicomponent epoxy resin. Its reactive temperature is between 18 and 25°C. It is used for high performance composite materials. A cure during 24 H at 70°C gives 80 % of maximal mechanical strengths for pure resin. (Modulus of rupture 750 daNmm^{-2}, Modulus of elasticity 35000 daNmm^{-2}).

To insure a good mechanical link, stainless steel pieces were moulded with the core barrel on each of its extremity.

Core barrel dimensions :

Length	8,3 m
Outer diameter	145 mm
Inner diameter	125 mm

WATER TANK

As for the core barrel, the water tank is made of composite materials. After a first fibreglass layer with teflon there are three layers : Kevlar - Carbon - Kevlar. A layer of epoxy resin with silica micro-bubbles gives a good thermal insulation. Its thickness is about 5 mm. Then there are three other layers : Kevlar - Carbon - Kevlar.

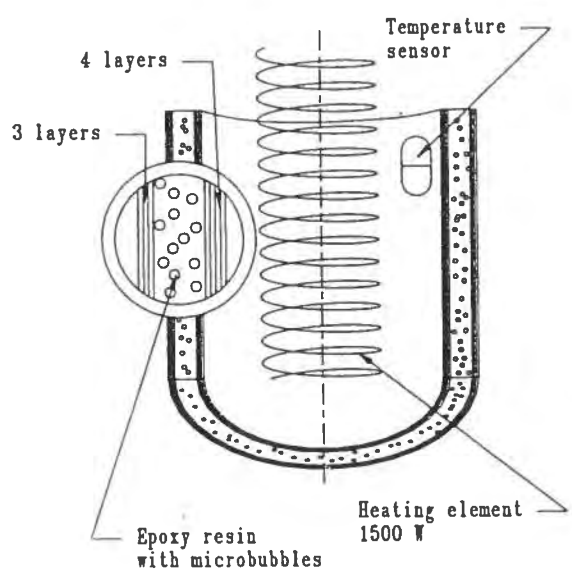

Figure 5 - Water tank

- **Single phase transformers** :

- Supply : Electronics, tube heater, tank heater, pump and electrovalve
- Surface tension fixed
- Out/put voltage is variable depending on the load
- Primary 1404 volts
- Secondary 335 volts

Dimensions :

Length	3 m
Outer diameter	130 mm
Inner diameter	125 mm

SUSPENSION

The suspension system is the top of the drill. It is directly connected to the cable. The cable is anchored with a double anchoring cone to the main piston. The piston holds the drill through a spring. A fluid shock absorber completes the spring action at its limit. It damps the stress when the ice core is extracted. The weight and the verticallity of the drill is controled through this connection. A threaded bush allows to regulate the tension of the spring.

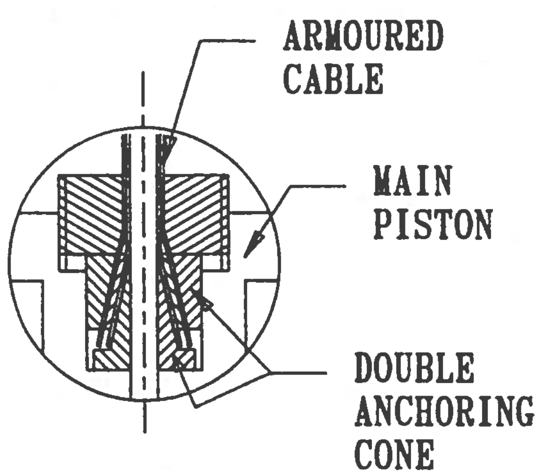

Figure 6 - Double anchoring cone

A sensor measures the linear displacement of the piston which is proportional to the pressure on the drill head. The top of the drill is centered by three pads maintained against the borehole wall. A second linear displacement sensor allows the measurement of the hole diameter through a link and a ring.

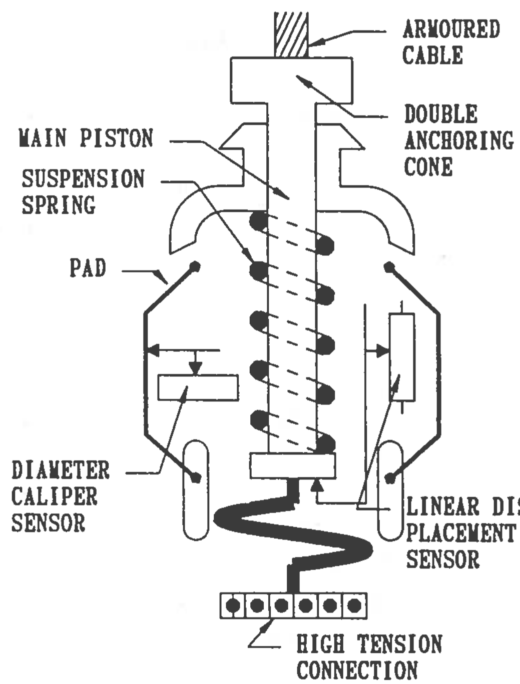

Figure 7 - Suspension

A high tension power unit supply allows to control supply voltage rapidly. All these elements are between three draw-bar. This set up allows adjustments, and manual interventions without disassembly.

Dimensions :

Length	1,5 m
Outer diameter	130 mm

Along the water tank axis, a bare electrical resistance wire heater is set up. It has a variable power along the axis to set a higher temperature at the bottom of the tank. Its maximum power is 1500 watts.

The control of the water filling is made by four temperature sensors located at different heights in the tank. This system gives informations on the pump running and the electrical power that has to be dissipated in the heating resistance.

Dimensions :

Length	5,8 m
Outer diameter	130 mm
Inner diameter	116 mm

PUMP AND ELECTROVALVE

The pump is connected to the top of the tank and sucks drilling fluid out of the tank. The electrovalve allows an air inlet at the top of the tank. A filter stops any particles which could disturb the pump operation. The pump flow is regulated by a manual valve. All these parts are standard industrial equipment.

Pump :
Electromagnetic pump GUINARD 2.9.300.10

- Power supply 220-230 volts
- Joints and ball valves : viton
- Suction head : 0,4 bars
- Tested several months in fluid at -60°C

Electrovalve :
Electrovalve JOUCOMATIC 14 00017

- Power supply 220-230 volts

Manual valve :
Valve SAGANA 2 F 4 AN

Filter :
Filter PORAL roasted bronze BL 32

Dimensions :

Length	0,5 m
Outer diameter	130 mm

ELECTRONIC COMPARTMENT

Electronic boards are fixed on stainless steel sections. The assembly is inside a fluid-tight compartment. This compartment resists 400 bars pressure.

The working of the electronics is described in "Telemetering and remote controls circuits for a 4000 m thermal drill" in this work.

Dimensions :

Length	2,8 m
Outer diameter	130 mm
Inner diameter	100 mm

TRANSFORMERS

Specially built transformers are located in a stainless steel tube. They are in an oil bath. A piston, which allows oil expansion, insures a seal with the outside.

Characteristics :

- **Triphase transformer :**

- Supply : drill head
- Surface tension 0 to 1236 volts
- Primary : 1236 volts
- Secondary : 60 volts

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SETTING UP A DEEP ICE CORE DRILLING FACILITY AND PRELIMINARY TESTS TERRE ADELIE - ANTARCTICA

by

Donnou D., Augustin L., Manouvrier A., Perrin J., Girard C., Ricou G.
Laboratoire de Glaciologie et Géophysique de l'Environnement du C.N.R.S.
St-Martin d'Hères, France

INTRODUCTION

The goal of the summer 1987-88 field operations was to test the thermal drill equipment designed to work in a fluid filled hole and developed at the LGGE.

At the laboratory we had at our disposal a 8 m deep ice pit but was not deep enough to run the assembled drilling system. Each of the six components was checked separately. The 22.4 m long assembled unit was operating for the first time in the field.

This drilling equipment should allow recovery of very deep ice cores during only one summer period, assuming that people work 24 h a day.

DRILLING SITE :
D47 (67°23'38"S, 138°43'31"E)

D47 is located in Adelie Land, 107 km from Dumont d'Urville and 1560 m above sea level.

This station has a mean annual temperature of -26°C and a snow accumulation rate of 26 cm H_2O yr^{-1}. The maximum observed wind speed is 34 m s^{-1}.

Difficulties encountered in the field were mainly linked to the bad climatic conditions prevailing in this area. During austral summer 1987-88 snow drift and wind were very strong and temperature varied between -25°C and -10°C.

WINCH (photo)

The winch is the heaviest piece of equipment. It weighs 6T and cannot be taken to pieces. The 4000 meter long cable is spooled on the winch drum using the Lebus system which allows spooling speed to vary from 50 to 90 m min^{-1}. The 75 kW hydraulic driving motor of 1979 cm3 generates at 400 bar a torque of 1258 m. daN. The maximum rotation speed is 120 rpm.

The winch is equipped with a static brake ensuring 944 m. daN. This brake operates in case of pressure loss or hydraulic circuit failure. The winding diameter is 700 mm and the drum width is 1100 mm. The rotation speed can be changed by using a pump with varying output and driven by a MOOG valve.

HYDRAULIC POWER-STATION

This power-station was designed to supply 95 kW at 3200 m a.s.l. At 2000 rpm, the thermal diesel motor (Deutz F8L413) supplies 135 kW. Electric power is considered to be decreased by 30 % at an altitude of 3200 m.

Four pumps are connected to the motor :

- the main one, with varying cubic capacity, drives the winch motor and is governed by a "Moog" servovalve (series n° 62),
- the second one is a 22 cm^3 per revolution auxiliary pump,
- the third pump is a 30 cm^3 p.r. auxiliary pump driving the hydraulic jack at high spooling speed,
- the last pump (4 cm^3 p.r.) supplies the winch motor braking unit.

TOWER (photo)

The tower, designed and built up to recover 8 m long ice cores below the drill, must support stress reaching 15 t during drilling operations and withstand wind as strong as 30 m s^{-1}. It is made up of seven floors 3.70 m high and 3 m wide. The five upper floors are similar, the two lower ones can be open on one side, allowing to free the core and to place it onto its support. Each floor section weighs about 350 kg.

A 4 m stroke hydraulic jack on which the counting wheel is fixed is fastened to the middle of the upper level by four arms. Slow hydraulic jack down motion is controlled by an electrovalve of varying output.

Assembling the tower requires 3 days work for six people. Fitting it out (power supply, hydraulic pipes, ladders, safety equipment) requires three more days.

MEASUREMENT EQUIPMENT OF THE DRILL UNIT

Thermal drilling produces water in amounts proportional to both section of the ice melted and core length. This melt water is stored in a tank.

Regular drill down motion and good core quality require continuous checking of the tank for : water inflow rate, level and temperature. Measurements are performed inside the tank by using platinium probes. They are recorded allowing to show more clearly when the fluid (DFA) - water interface arrives as fluid temperature is negative and water temperature is positive (see fig. 1). Water level reaching 50 mm below the 6 th. probe means that the tank normally fills. If the water didn't reach this probe within a well defined time, efficiency of the fluid circulation inside the drill must be suspected and all required tests must be performed.

The first probe is located close to the tank inlet just at the top of the pipes and is used to check the drilling fluid circulation and temperature inside the tank ; this probe also allows to adjust the power to the resistance heaters for the suction pipes which are fastened around the drill barrel. Temperature between 10 and 15°C at the pipe outlet provides good results.

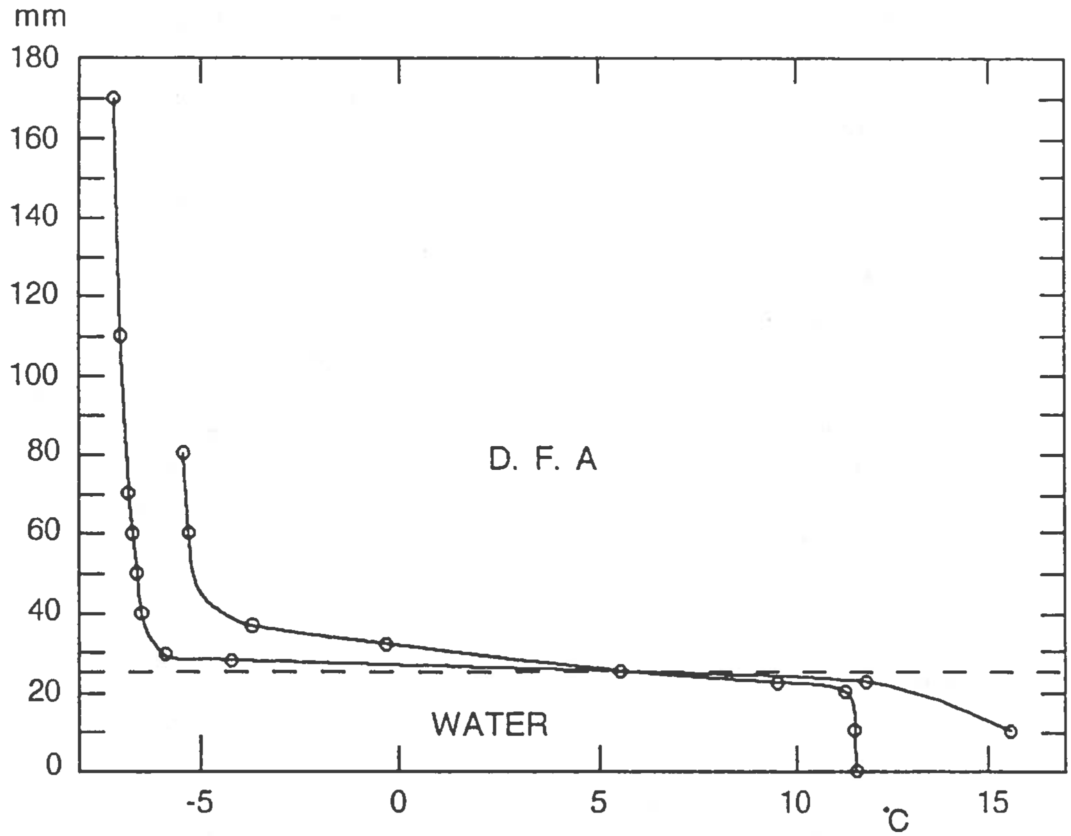


Fig.1 - Temperature profile at the water-DFA interface

Tower assembly

Winch

DEEP ICE CORE DRILLING EQUIPMENT DEPTH MEASUREMENT AND DRILLING PROCESS

by

PERRIN J.
Laboratoire de Glaciologie et Géophysique de l'Environnement du C.N.R.S.
St-Martin d'Hères, France.

The deep drilling equipment developed by the LGGE includes, apart from the core drill itself, a winch and a drilling tower on top of which is erected a 4 m stroke hydraulic cylinder supporting the sheave.

There are two means to move the drill up and down :

- the winch for high-speed raising and lowering of the drill ;
- the hydraulic cylinder for control of penetration, core breaking and core recovery at the surface.

It's then difficult to measure the depth with accuracy because of the two kinds of movement :

- the sheave rotation
- the hydraulic cylinder linear displacement.

We solved the problem by the use of an optical encoder and auxiliary sheave with the same diameter as the main one. The optical encoder axle is connected to the main sheave's one. Its case is fixed to the auxiliary sheave and is equiped by a slip ring assembly. When using the hydraulic cylinder, the two sheaves rotate in opposite ways.

Both the hydraulic cylinder and the winch can be used simultaneously, whatever their relative movement.

The encoder delivers four different signals :

- 2 counting tracks A and B with 200 impulses per revolution out of phase of 90°
- 1 Up/Down signal
- 1 inverting Up/Down signal.

A digital sequential processor is used for two mean functions :

- the permanent control of the encoder and of the measured depth
- the automatic positioning of the drill in the bore hole and on the surface during setting up or core recovery.

Control phase : The processor permanently controls the encoder signals. It informs the operator when a counting fault occurs. A logic processor allows to locate exactly the fault and its origin. This makes the maintenance interventions easier.

Automatic drill positioning system acts as follows : The first cycle allows the drill positioning at the bottom of the bore hole. The second cycle allows the drill positioning at the surface. The winch rotation speed depends on the drill position in the hole. This rotation speed is determined by comparison between the drill depth and reference depth values. The first counter value increases when the drill is lowered and is equal to zero at the surface. The second counter value increases when the drill is raised and is equal to zero at the bottom of the hole. The two counters reset automatically.

A control terminal allows modification at all the parameters, such as :

- depth reference values
- timing
- counter value comparators.

TELEMETERING AND REMOTE CONTROL CIRCUITS FOR A 4000 m THERMAL DRILL

by

MAREC G., MAITRE M., PINGLOT F., LEFEBVRE E.
Laboratoire de Glaciologie et Géophysique de l'Environnement du C.N.R.S.
St-Martin d'Hères, France.

Handling water make thermal drills rather tricky to use. People operating such a drill in very cold ice face with two main problems :

- know at any time what is going on in the drill,
- be able to operate from the control desk in surface a few apparatus located in the drill.

In order to improve reliability of our 4000 meters thermal drill, researches have been carried on about specific telemetering and remote control electronic circuits.

Purpose of this paper is to give a few informations about two tests systems designed in order to compare reliability, efficiency, implementation and use of two transmissions principles, one using a frequency division multiplexing and the other a time division multiplexing principles.

A third final system should be designed after the first field tests taking very likely into account both transmission principles.

I - DATA AND DRIVES TO BE TRANSMITTED

A good monitoring of the 4000 meters thermal drill needs the transmission of 13 data or drives between the drill and the control desk. Sharing out of these signals is given below .

I.1 - Data travelling up from the drill to the control desk

- 6 temperatures data from 4 transducers in the water tank, 1 transducer near the heating head and 1 transducer in the electronic tank.
- 1 position data from the position transducer of the drill suspension.
- 1 diameter data from the transducer giving the size of the borehole.

I.2 - Drivings travelling down from the control desk to the drill

- 2 proportional drivings to operate heaters in water tank and pipe.

- 2 Go / No Go drivings to operate the pump and the electrical valve.

- 1 Go / No Go test driving used to check the overall transmission. When this test is actuated all temperatures displays are shifted by an equal amount of + 20°C, apart temperature data from the electronic tank which is set to 0°C.

  This test is intended to be used very easily while drilling in the field when the driller feels something wrong in the overall drill behaviour and wants to make sure data or drivings transmissions are not failing.

2 - CONNECTION BETWEEN THE DRILL AND THE SURFACE DESK

The main cable which hangs and feeds the drill is made up of 8 wires for all power supplies and a bifilar pair for data transmission.

2.1 - Data transmission line

The bifilar twisted pair has not been specially designed for data transmission. It is made up of two 0,34 mm^2 wires, teflon insulated, with no screen. Frequency cut-off of this line is of course load depending as indicated below at 3 db down :

2.5 kilohertz under 600 Ω
4.5 kilohertz under 300 Ω
8 kilohertz under 150 Ω
12 kilohertz under 100 Ω

Loading of 150 Ω has been chosen in order to be able to operate the line to about 24 kilohertz.

2.2 - Power supply

Among the 8 wires of the cable 6 are used to supply the heating head and 2 as a secondary power line to supply electronic driven apparatus and the electronic compartment.

Although a high voltage had been used to transmit power along the 4000 meters cable, the voltage drop is very important and the power supply level varies between 220 and 340 volts depending on heating power in the water tank and pipe.

This high power supply swing has made the electronic power supply circuit more difficult to design and increased its size.

3 - TRANSMISSION PRINCIPLES

As previously mentioned two very different transmissions systems have been designed and built. The first one uses a frequency division multiplexing technique (in short FDM) and the second one, which has been designed a bit later, a time division multiplexing (in short TDM). In order to save time and money the second design uses the same signal conditionners as the first one.

3.1 - Frequency Division Multiplexing (FDM)

In this mode of transmission :

- each data is converted into a modulated wave

- all waves are continuously sent on the transmission line by the transmitters

- the receivers convert back all waves in DC levels

- 13 frequency bands are necessary in this design.

  Main advantage of this mode of transmission is the possibility of making all transmissions channels fully independant. One channel can fail, because failure of an electronic component for instance, without any effect on the others.

  Main disadvantage is of course larger design and tuning times.

3.2 - Time Division Multiplexing (TDM)

In this mode of transmission :

- each data is sampled and converted into a binary word or level

- two microprocessors circuits are used acting as transmitters and receivers (drill and desk)

- transmission is operated in half-duplex mode, the reason will be given later

- modulators and demodulators are used because the length of the transmission line

- 3 frequency bands are necessary.

  Main advantage of this mode of transmission is the flexibility of software operated electronic circuits and a rather shorter design time.

  Main disadvantage is the risk of overall transmission failure if any electronic component is failing.

Figure 1 shows a very simplified block diagram of overall transmission systems including both FDM and TDM design.

Upper part of the diagram relates to the transmitter and the receiver laid in the control desk and the lower part to the corresponding circuits in the drill.

Boxes with slash indicate differences of design in the two systems : above the slash relates to the FDM circuits and below the slash to the TDM.

Other boxes represent identical circuits in both design ; monitor is of course not used in FDM.

In the lower part of the diagram, the switch between the "signal conditionners" box and the "converters or DAC" box is the test switch operated from the control desk "signal conditionners".

4 - THE FDM TEST SYSTEM

Three kinds of transmission channels have been designed to fulfill all requirements :

- data channel
- proportionnal driving channel
- Go / No Go driving channel.

4.1 - Data transmission

A simplified block diagram is given Fig. 2.

- Transmitter :

Transducer is DC supplied and signal is amplified by an instrumentation amplifier. DC signal is then sent to a voltage/frequency converter the output of which is a frequency variable square wave.

Supply of transducer, instrumentation amplifier and V/F converter constitute the signal conditionners shown Fig. 1.

The frequency variable square wave drives a frequency shift keying modulator whose output signal is sent to the transmission line after been filtered in order to shrink its frequency span.

In this test system only one amplifier has been used to drive the transmission line and all transmitted signals are mixed in front of the amplifier. In order to improve reliability it would be very easy to use one output amplifier in each channel and to mix all transmitted signals in front of the coupling transformer.

- Receiver :

The demodulator is a phase locked loop based circuit which restores the frequency variable square wave. Input filter is mandatory to avoid locking the loop on a bad frequency.

The square wave is then sent to a frequency to voltage converter restoring the DC level which is displayed.

4.2 - Proportionnal driving transmission

This circuit is very similar to the previous one ; a simplified block diagram is given Fig. 3.

- Transmitter :

Electronic circuit is the same. The only differences lies in the use of a DC supplied potentiometer at the input instead of a transducer.

- Receiver :

Electronic circuit is the same too. DC output level of the F/V converter is sent to a power controler instead of being displayed.

- Power controler :

Block diagram of this circuit is given Fig. 4. Purpose of this circuit is to transform a low power continuously tunable DC level into a proportionnal high power AC level in a heater. It has been rather difficult to design a very reliable circuit. Two problems were to be solved :

- switch on the heater as near as possible the zero crossing point of line voltage in order to avoid generation of RFI signals
- switch on the thyristors at very low operating temperature under this very low voltage level.

4.3 - Go / No Go Driving transmission

This circuit is the simplest. Block diagram is given Fig. 5.

- Transmitter :

There is no need for a filter between the modulator and the transmission line because output signal is a pure sinusoïdal wave.

- Receiver :

Binary output signal of the PLL demodulator drives a switch controler.

- Switch controler :

This circuit is used to switch on and off a reed relay used to feed a low power, line supplied, apparatus (pump or electrical valve).

A reed relay has been used instead of a thyristor because power dissipated in the load is far too small to keep a thyristor switched on at lowest operating temperature. In order to avoid fast burning of reed relay's contacts, this switch controler has been designed to switch off at zero current level in the inductive load.

A block diagram of this switch controler is given Fig. 6.

4.4 - Frequency bands used in the FDM test system

Informations about filters center frequencies, frequency span and use of the 13 channels are given on Table 1.

4.5 - Operating conditions of the FDM test system

- Temperature rangs :

-55°C to +35°C (limit temperature of laboratory test)

- Drill circuits operating voltage supply :

200 to 340 volts RMS

- Transmission accuracy :

$\pm 10^{-4}$

- Power consumption :

Drill circuits 80 watts under 220 volts
Desk circuits 60 watts under 220 volts.

5 - THE TDM TEST SYSTEM

5.1 - Time Division multiplexing principle and digital serial transmission

The device includes two microprocessor circuits for the surface desk and the drill electronics. Five (up to eight) proportional controls are sent to the drill, and simultaneously eight measurements are transmitted up to the surface, both at a rate of ten exchanges per second on the cable, in a serial mode. For this purpose, a modem circuit, working in a half-duplex asynchronous mode, transmits at 2400 Bauds, with a frequency shift keying (FSK) modulation on the three channels at 4, 8 and 16 KHz (including the reset function) (Table 2).

Half-duplex has been temporary used in this test system in order to shorten transmission working time of microprocessors too much used to measure the frequency of signals to be transmitted.

5.2 - Hardware design (Fig. 7)

- Central processing units (C.P.U.)

The two C.P.U. used are 8 bits CMOS devices (National Semiconductor : NSC 800 M) choosen for their Z 80 instructions set, low-supply current and military temperature range (working at 2 MHz). The surface electronic contains Euronorm printed circuits, specified for ruggedized applications (mechanical and temperature down to -40°C). CIMBUS cards (CMOS industrial micro-computer bus from N.S.) are installed in a water-proof 19"-3U cabinet and including : C.P.U., Memory expansion, UART for C.R.T. terminal, D.A.C. These later cards are alltogether connected on the BUS, and four other cards are used as signal conditionners and low voltages power supplies.

The drill C.P.U. board is a multi-layer C.A.D. printed circuit, using MIL grade integrated circuits. Each C.P.U. includes PROM and RAM devices (up to 64 K bytes), as well as 8 bits parallel input-output ports (P.I.O.), timers and analog to digital converters (and inversely). After, or before digital conversions, the conditionner circuits as well as the power commands (proportional or Go - No Go) are similar to the devices designed in the multiplexing frequency principle, as well as the overall test circuit.

- Serial mode of transmission (Fig. 8)

For these first tests, the system software is designed for half-duplex asynchronous mode of transmission, at 2400 Bauds rate.

After analog to digital conversions, the controls and measurements are available the 8 bits C.P.U. bus. A U.A.R.T. circuits (RCA CDP 1854) converts the 8 bits data from parallel to serial mode, in order to transmit the informations on the bifilar pair, in a time-multiplexing modulation final mode.

At the U.A.R.T. output, the binary pulses are F.S.K. modulated (EXAR : XR 2206 M), and after amplification transmitted to the 4000 m cable, using a transformer coupling ($Zc = 150\ \Omega$).

The central F.S.K. frequencies (4, 8 and 16 KHz, respectively for the transmission of the reset of drill C.P.U., the remote controls to the drill and the transmission of the measurements up to the surface desk) are 25 % (mark and space frequencies) modulated. At the reception of the FSK signal, 4 th order band-pas Butterworth filters (making use of switched capacitor filters integrated circuits : NS, MF 10 M) are operated from a stable clock oscillator working at 6,4 MHz.

5.3 - Software of the microprocessors

Three possible modes of operation are assumed by the software :

- Surface monitor and assembler dialogue with C.R.T. terminal
- Surface to drill transmission
- Complete telemetering and remote control of drill.

The software contents the following tasks, the surface desk C.P.U. software acting as the master program relative to the slave program of the drill C.P.U.

- Monitor program
- Z 80 assembler
- Specific programs including : data acquisition (analog to digital and inversely) of up to eight measurements from the drill and up to eight remote commands to the drill ; the serial communications in both directions ; C.R.T. terminal interactive dialogue with unit conversions and screen display, and the general control of the transmission (error of transmission message by C.R.C. determination and a watch-dog message if no exchange occurs on the cable for at least 0.5 s).

5.4 - Operating conditions of the T.D.M. test system

These operating conditions are the same as in the FDM test system concerning temperature range, drill circuits operating voltage supply. However, the overall transmission accuracy (for the complete temperature range) is about 0.5 %. About the power consumption, both drill and desk circuits draws less current (CMOS circuitry).

5.5 - Future extensions

Although preliminary tests need to be conducted with the drill itself, future extensions may consist of :

- depth measurement of drill
- increased accurary, presently limited to 8 bits equivalent, increased speed of transmission (exchanges per second), number of measurements and remote controls (eight each actually)
- use of a dedicated microprocessor for improved C.R.T. dialogue
- software including full-duplex mode of transmission
- automatic servo-loops and regulations for proportionnal or Go / No Go remote controls.

A much appreciated fruitful cooperation, and the software development of the Time Division Multiplexing device, have been conducted with Jean-Paul Eynard, Jack Baudoin and Fidèle Andrianandraina (joint C.N.R.S. - I.N.P.G. program).

5 - CONCLUDING REMARKS

The FDM system has been used for the first time in Antarctica during the field party 1987/1988 at D47. All the field tests were very good and these circuits have been successfully used again during the 1988/1989 campaign at D74 where the 4000 meters drill did reach -871 meters depth. The FDM system proved to be very reliable, accurate and easy to operate.

First test of the FDM system made during the 1988/1989 field party did point out transmissions problems although laboratory tests were good. It has not been possible to find the reason of these problems in the field, a few other laboratory tests are necessary.

CHANNEL	FILTER CENTER FREQUENCY	FSK SPAN	USE
1	350	332 - 368	TRANSMISSION TEST
2	500	475 - 525	ELECT. VALVE SWITCH
3	700	665 - 735	PUMP SWITCH
4	1000	950 - 1050	Θ° DRILL
5	1400	1330 - 1470	Θ° DRILL
6	2000	1900 - 2100	Θ° DRILL
7	2800	2660 - 2940	Θ° DRILL
8	4000	3800 - 4200	Θ° DRILL
9	5600	5320 - 5880	HEATER
10	8000	7600 - 8400	Δ SUSPENSION
11	11200	10640 - 11760	HEATER
12	16000	15200 - 16800	Θ° ELECTRONIC CIRCUIT COMPARTMENT
13	22400	21280 - 23520	ø BOREHOLE

Table 1 - Frequency bands (Hz) used in the FDM test system

CHANNEL	FILTER CENTER FREQUENCY	FSK SPAN	USE
1	4000	3500 - 4500	RESET DESK DRILL
2	8000	7000 - 9000	TRANS. DRILL DESK
3	16000	14000 - 18000	TRANS. DESK DRILL

Table 2 - Frequency bands (Hz) used in the TDM test system

_TRANSMISSION PRINCIPLES
FDM AND TDM

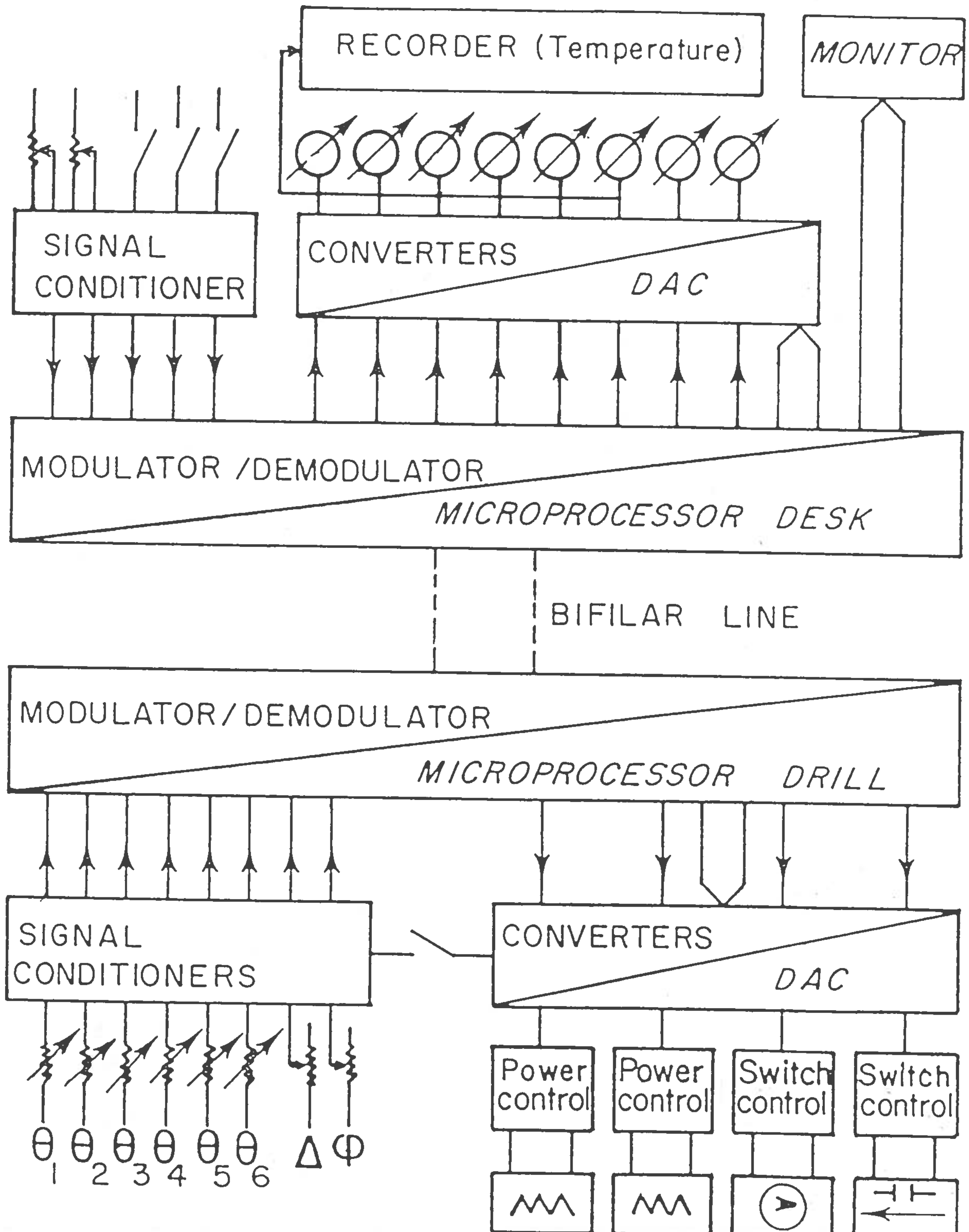


Fig.1

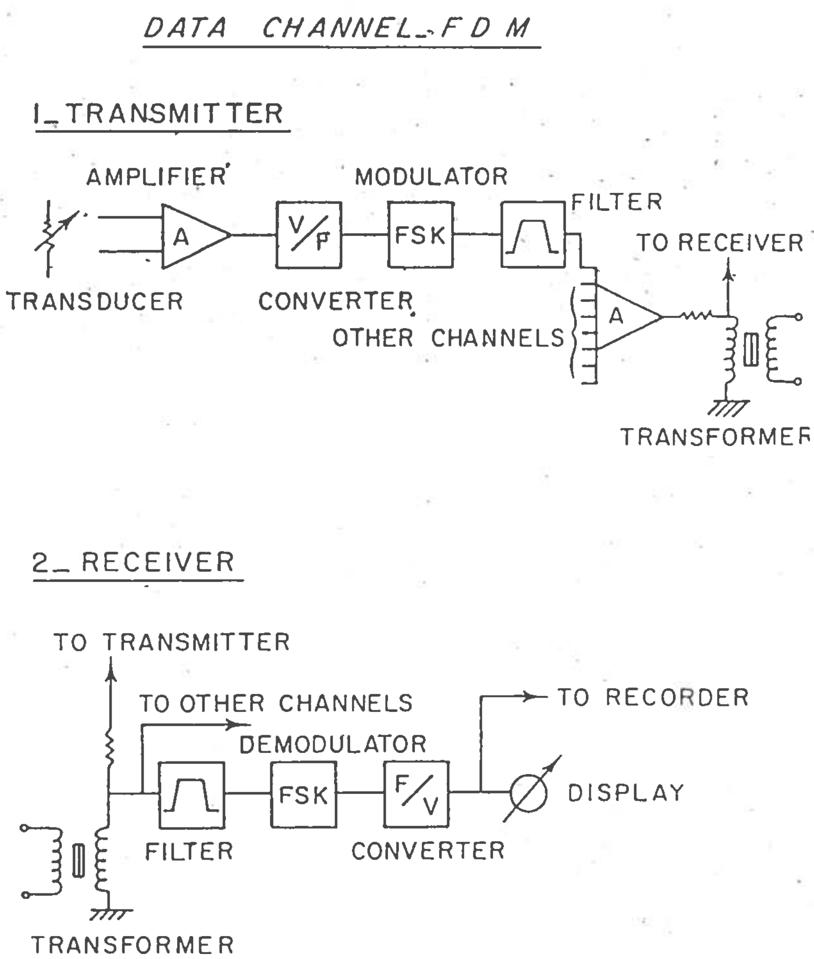

DATA CHANNEL_FDM
1_TRANSMITTER
AMPLIFIER
MODULATOR
FILTER
V/F
FSK
A
TO RECEIVER
TRANSDUCER
CONVERTER
OTHER CHANNELS
TRANSFORMER
2_RECEIVER
TO TRANSMITTER
TO OTHER CHANNELS
DEMODULATOR
TO RECORDER
FSK
F/V
DISPLAY
FILTER
CONVERTER
TRANSFORMER

Fig.2

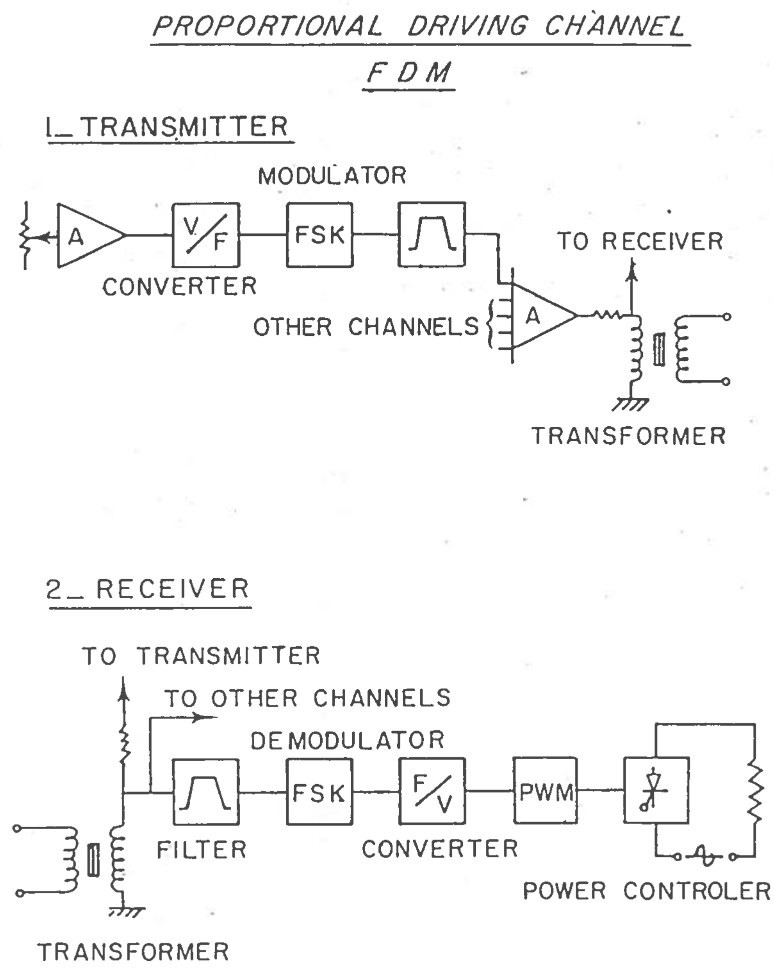
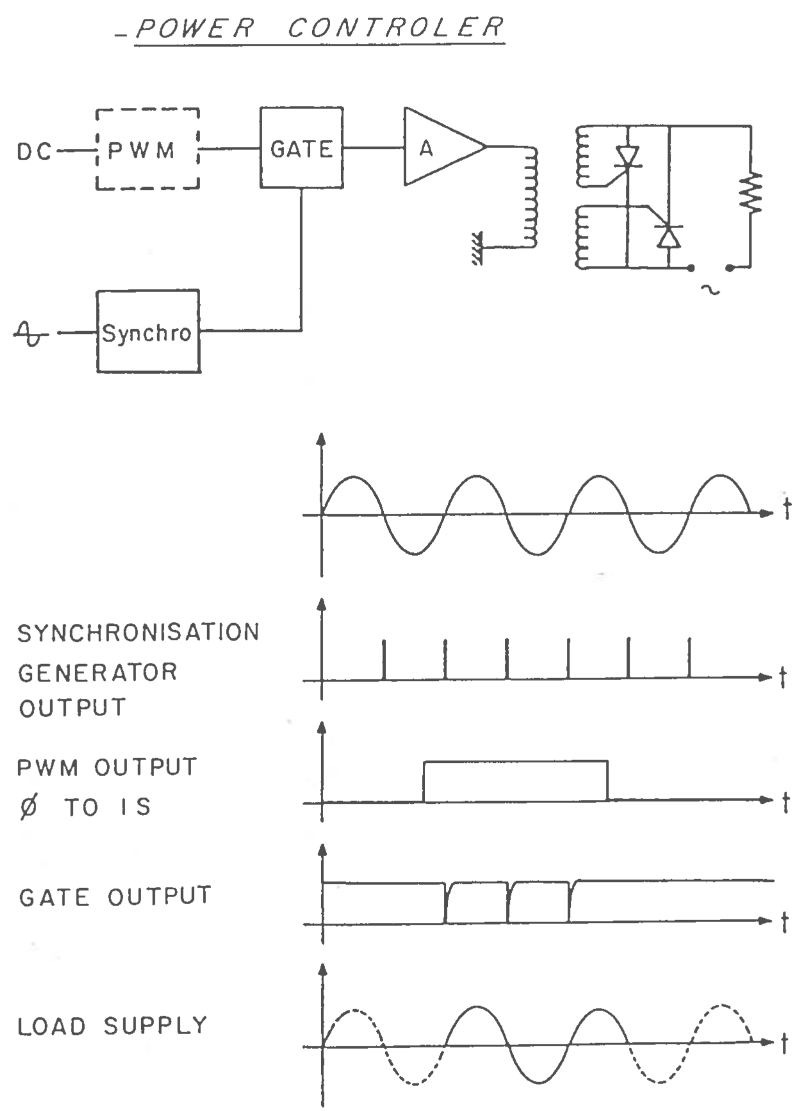
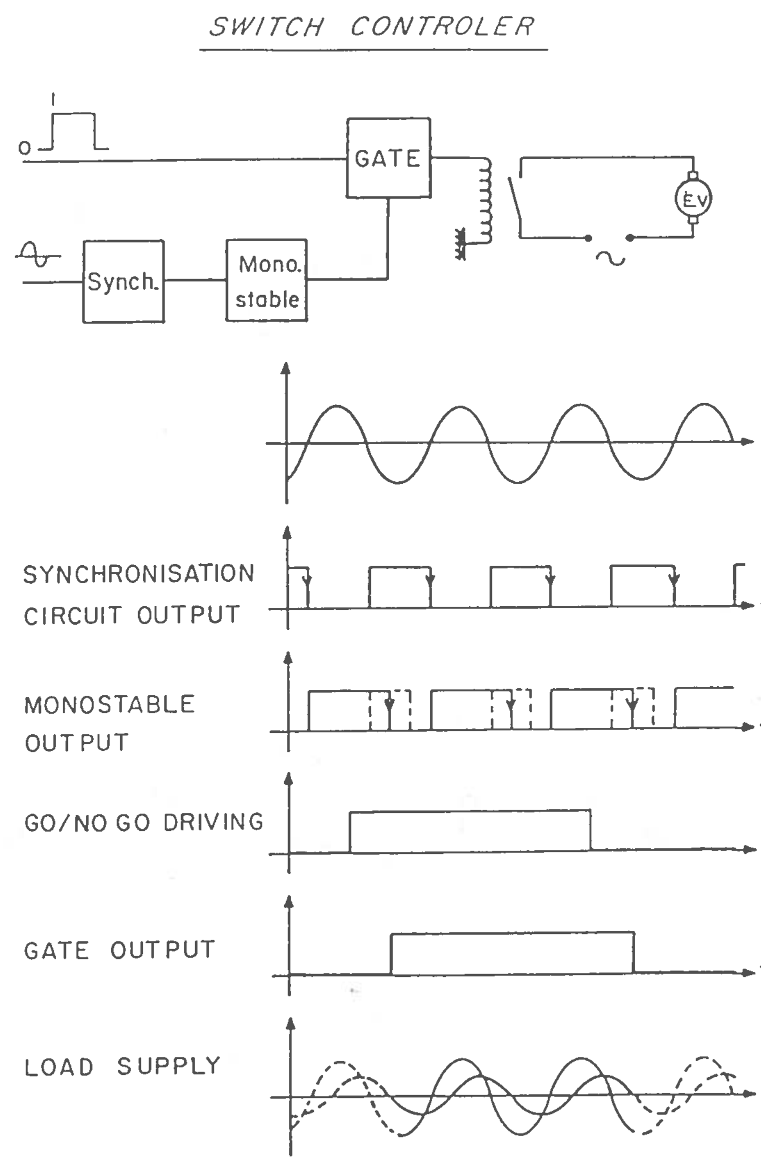

PROPORTIONAL DRIVING CHANNEL
FDM
1_TRANSMITTER
MODULATOR
A
V/F
FSK
TO RECEIVER
CONVERTER
OTHER CHANNELS
TRANSFORMER
2_RECEIVER
TO TRANSMITTER
TO OTHER CHANNELS
DEMODULATOR
FSK
F/V
PWM
FILTER
CONVERTER
POWER CONTROLER
TRANSFORMER

Fig.3



_POWER CONTROLER
DC
PWM
GATE
A
Synchro
SYNCHRONISATION GENERATOR OUTPUT
PWM OUTPUT Ø TO IS
GATE OUTPUT
LOAD SUPPLY
t

Fig.4



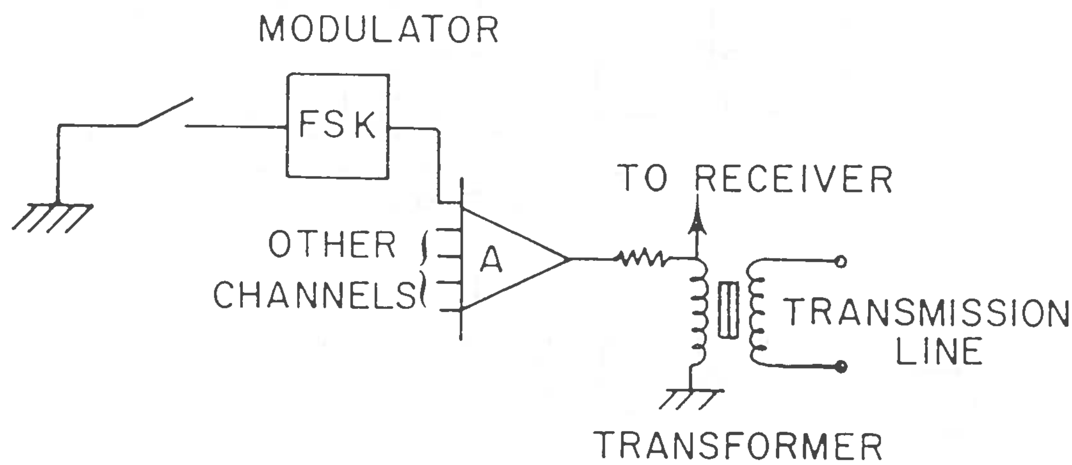
SWITCH CONTROLER
0
1
GATE
Synch.
Mono. stable
Ev
SYNCHRONISATION CIRCUIT OUTPUT
MONOSTABLE OUTPUT
GO/NO GO DRIVING
GATE OUTPUT
LOAD SUPPLY
t

Fig.6

GO/ NO GO DRIVING CHANNEL

F D M

1_TRANSMITTER



2_RECEIVER

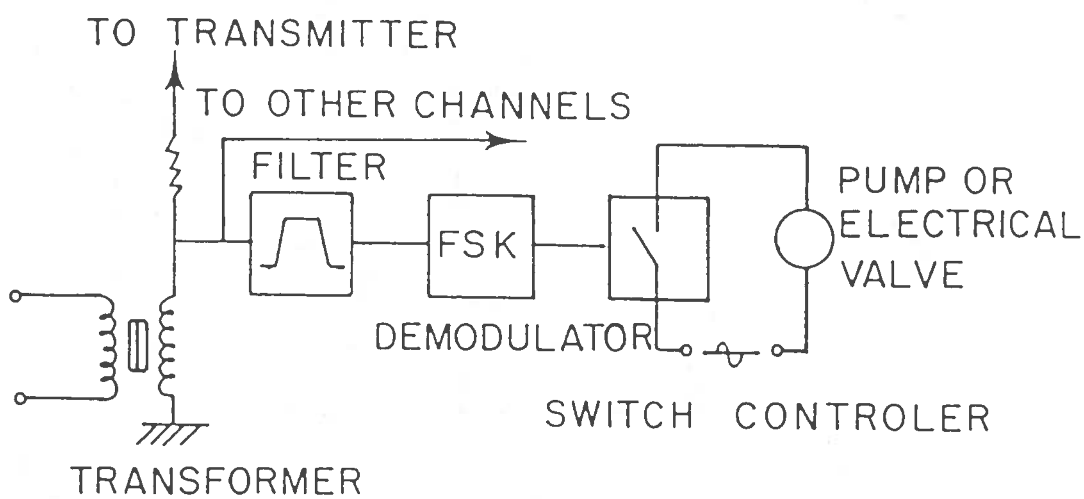


Fig.5

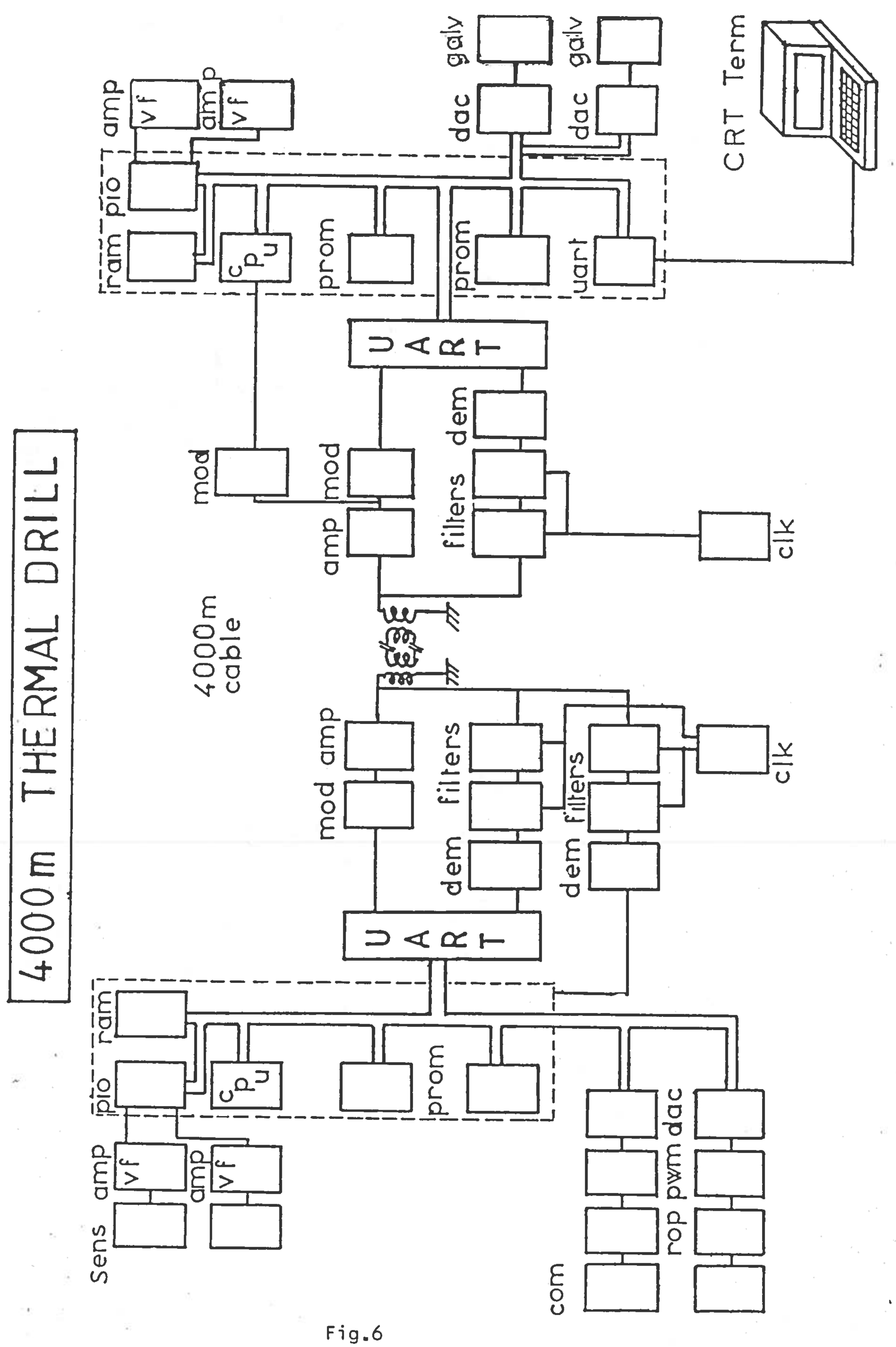

4000m THERMAL DRILL
4000m cable
Sens
amp
vf
pio
ram
cpu
prom
UART
mod
amp
filters
dem
clk
com
rop
pwm
dac
galv
uart
CRT Term

Fig.6

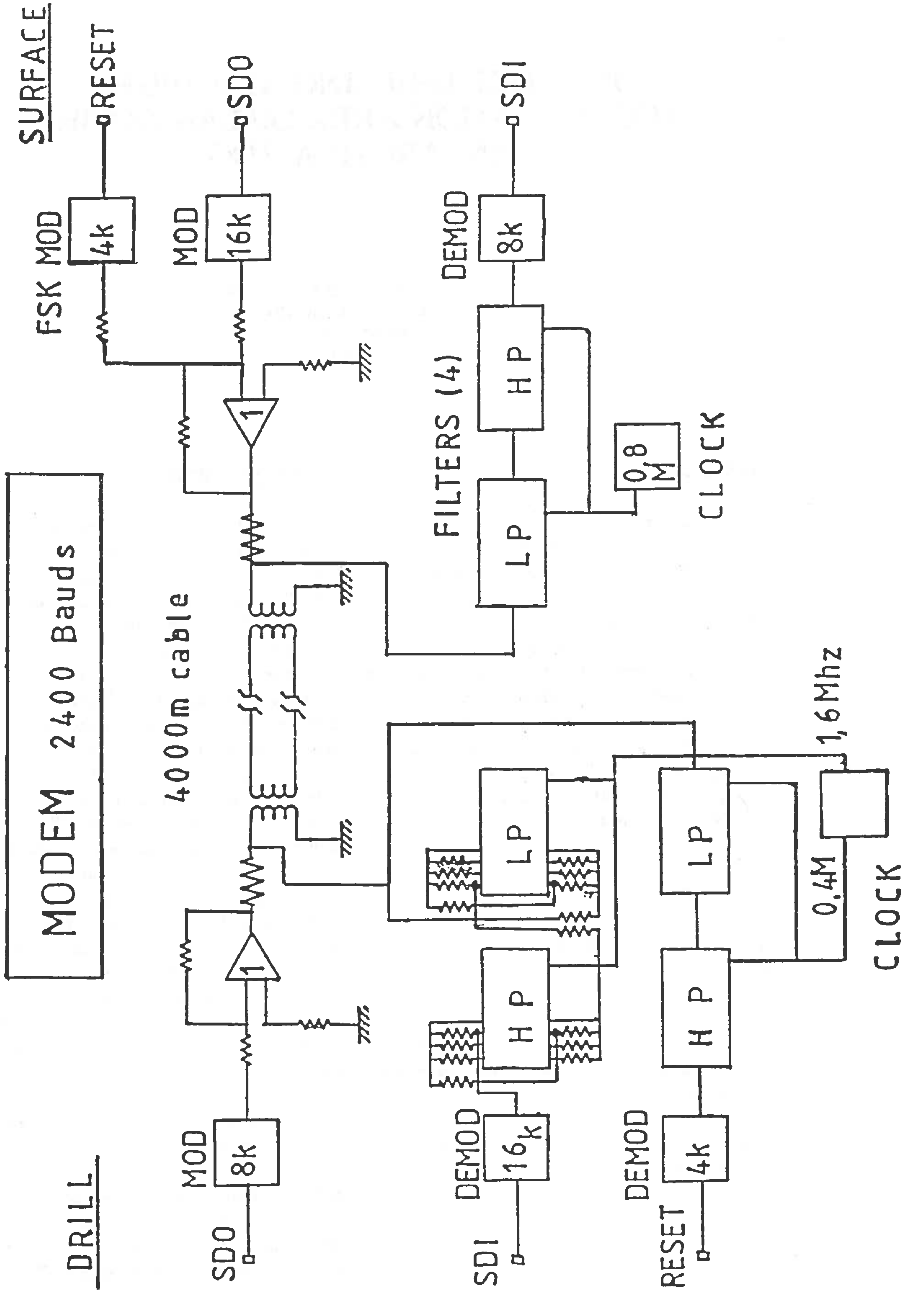

MODEM 2400 Bauds
SURFACE
DRILL
RESET
FSK MOD
4k
SDO
MOD
16k
SDI
DEMOD
8k
FILTERS (4)
HP
LP
0,8 M
CLOCK
4000m cable
1
MOD
8k
DEMOD
16k
DEMOD
4k
RESET
1,6Mhz
0,4M
CLOCK

Fig.7

ICE CORE DRILLING AT A HIGH ACCUMULATION AREA OF LAW DOME, ANTARCTICA, 1987

by

D.M. Etheridge and C.W. Wookey
Australian Antarctic Division
Channel Highway, Kingston, 7050.
Australia.

ABSTRACT

A 234 metre deep, 195 mm diameter ice core was drilled at DEO8, 16 km east of the summit of Law Dome summit in 1987. The details of the thermal drill facility are described. The ice core and borehole were measured and sampled on-site for all principal parameters and showed that the core reached back to about 1810 AD. The snow accumulation rate at the drill site is about 1200 kg m^{-2} a^{-1} and surface melting is very infrequent. The suitability of the core for gas composition studies and other analyses is discussed.

1 - AIMS

The aims of the 1986/87 ice core drilling at DEO8 were :

(i) to obtain an ice core from a cold, high accumulation zone suitable for analysis of recent changes in atmospheric trace gas composition ;

(ii) to test and develop a large diameter thermal drill ;

(iii) to test and develop an on-site core analysis scheme.

2 - BACKGROUND

Ice core drilling yields ice that contains information on past climates, atmospheres and terrestrial conditions on timescales of tens of years to hundreds of thousands of years. Of particular interest is the recent increase in the concentrations of some atmospheric trace gases which may contribute to the greenhouse effect. These gases (carbon dioxide, methane and nitrous oxide) have been measured in the air trapped as bubbles in ice cores (Barnola and others, 1987 ; Etheridge and others, 1988 ; Neftel and others, 1985 ; Rasmussen and Khalil, 1984). However, the age resolution of the ice core air has not been fine enough to allow precise comparison of the ice core results with recent direct readings which began as late as the last decade for some atmospheric species. This comparison would test the accuracy of the techniques used to extract and analyse the air and whether the air's composition changed whilst enclosed in the ice.

The age resolution of the air trapped in an ice sheet is predominantly a function of the snow accumulation rate and is normally deduced from the number of years over which 80 % of the air is trapped (Schwander and Stauffer, 1984). This is parameterised by density, where 795 kg m^{-3}

is defined as the density at which 10 % of the total air is trapped as bubbles and similarly 830 kg m^{-3} for the 90 % level. By drilling a core at DEO8, where the accumulation rate is about 1200 kg $m^{-2}a^{-1}$, (c.f. 650 for the Law Dome summit core BHD, 500 for Siple Station and 22 for Vostok), trapped air with an age resolution of about 8 a can be found. This compares favourably with other sites that have been analysed for gas composition : 17 a for BHD (Law Dome summit), 22 a for Siple Station and Dye 3, 370 a for Dome C and 590 a for Vostok. The precision of the DEO8 air dating should thus allow accurate calibration of the ice core gas record.

3 - THE DRILLING SITE

The DEO8 borehole (-66°43'19", 113°11'58", 1250 m.a.s.l., in April 1987) lies 16 kilometers east of the summit of Law Dome (Figure 1). Orographic effects create the high accumulation which increases rapidly going east from the summit. The ice thickness is about 1180 metres and because of the site's proximity to the ice divide, deformation due to shear is small especially in the upper region of the ice sheet. Thus, annual layers are well preserved. The mean annual temperature (i.e. 10 metre firn temperature) is about -19°C. The surface is smooth and soft, and the prevailing wind is from the ESE, which is also the direction from which most of the site's precipitation comes.

The site was first investigated by A.N.A.R.E. (Australian National Antarctic Research Expedition) in 1984. In 1985 a 46 metre core was drilled in the region, the results of which created interest in drilling further.

4 - DRILL FACILITY

The drill was a cable-supported thermal drill. Its design and method of operation was similar to the CRREL thermal drill as modified by Bird and Ballantyne (1971), but the dimensions and construction were quite different. It drilled a larger diameter hole (260 mm diameter c.f. 170 mm) to accommodate the borehole casing required by the electromechanical deep drilling system to be used in the future. It also took a larger diameter core (195 mm), which has many advantages for core analysis. It operated in a dry borehole.

The melt head consisted of a single-phase electric element, vacuum brazed to a copper substrate and bolted to a steel housing. The element could dissipate up to 3.5 kW. Six core 'dogs' (used to sever and catch the core) were housed in the head which was threaded on to a fibreglass drill barrel capable of taking a maximum core length of 1.95 metres. Melt water was sucked up heated tubes into an evacuated water tank above the drill barrel. The vacuum pump and electronics for drill telemetry (head current and temperature, water tank vacuum) and drill feed were contained in a module on top of the water tank. A 'Pajari' borehole surveying instrument was also housed in the module. The 12 mm diameter winch cable consisted of a double spiral outer sheath surrounding seven insulated conductors. The winch cable passed over a pulley, mounted on a hydraulic ram and was terminated at the drill in a suspension device. This device divided the weight of the drill between the cable and melt head by continuously triggering a valve which lowered the hydraulic ram during drilling. In this way smooth, controlled feed could be maintained and the hole could be kept vertical.

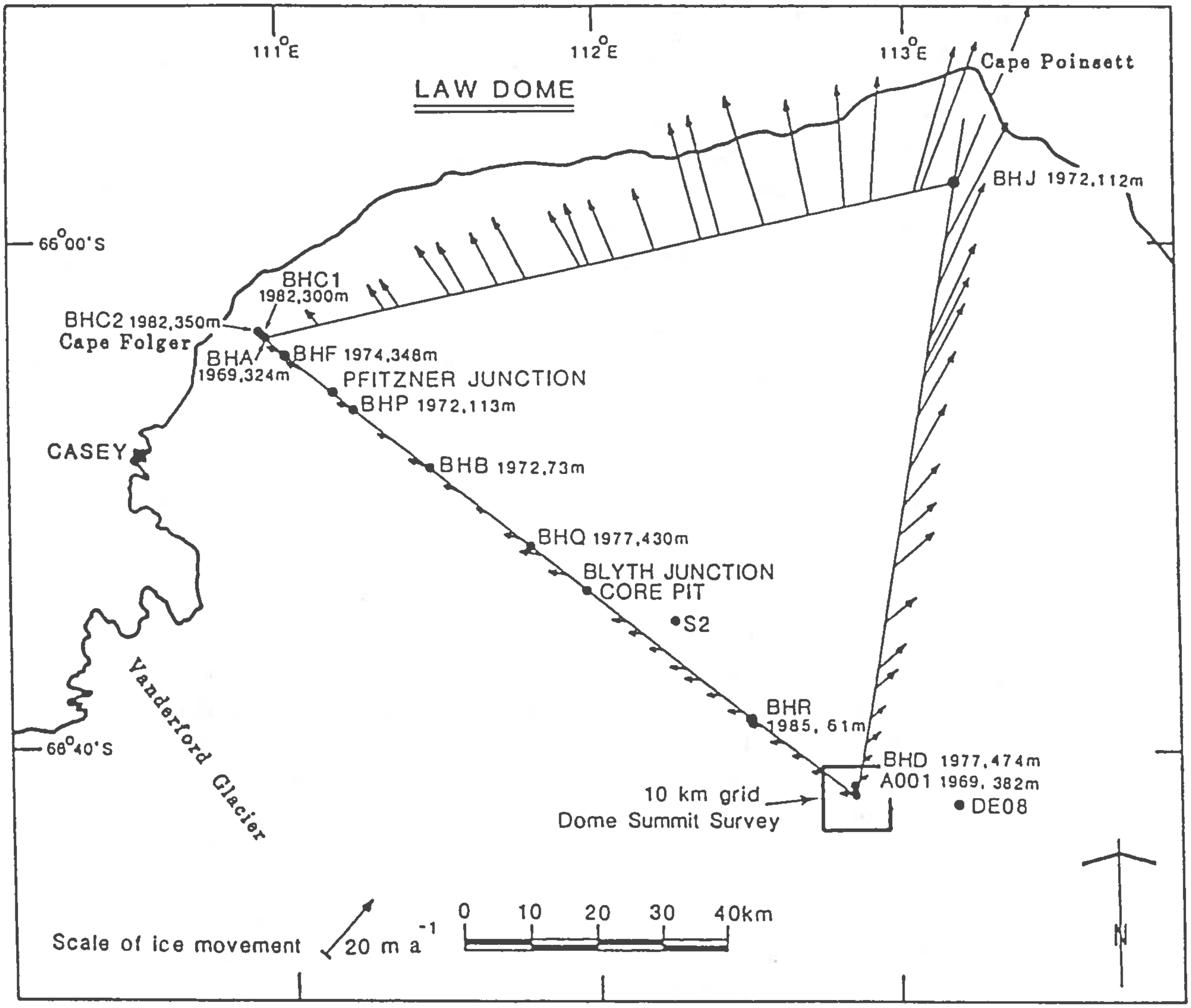


Figure 1 - Map of Law Dome, showing borehole locations and surface velocity vectors.

To assist breaking off such large cross section cores, a prototype device was incorporated in the top of the core barrel. This consisted of a powerful solenoid with a massive iron core. When tension was applied to the cable to withdraw the drill and core, the solenoid was energised, creating an impact that was transferred through the core dogs to sever the ice. The core barrel was suspended on rubber mounts to increase the effect. Although useful in some applications, the deeper, brittle ice cores were often damaged by severing cores in this way.

At the surface, the winch, hydraulics and drill controls were housed inside the fully enclosed 'drill van', which was set on a sled. The drill tower lay flat on the drill van roof until the drill site was reached where it would be raised hydraulically.

5 - DRILLING PROCEDURE

A typical coring run began with drill preparation : the hydraulic feed ram was raised, the core dogs were released, the melt water tank drains were close and the Pajari instrument set. The drill was then positioned above the hole and the depth counter set to zero. The electrics were switched on and the head current set to about 5 A before the drill was lowered.

When the drill reached the bottom of the hole, the head current was increased to 15A, the automatic feed was enabled and the drill was raised slightly until the feed was trigged. The head temperature would then increase, which would then be followed by a rise in vacuum, a drop in head temperature and the beginning of drill feeding. Drilling ceased when the top of the core met the end of the core barrel and stopped the drill feeding.

The method of severing the core depended on the type of ice encountered. Firn cores would normally sever cleanly by just retracting the drill after making sure the core dogs had caught. Ice was harder to sever, requiring more force and sometimes 'necking' - narrowing the end of the core by melting but not feeding. Using force to sever brittle cores however would usually shatter the ice. Instead, the core would be necked right through and then carefully lifted. The amount of tension on the winch cable was a valuable guide to the drilling and severing processes.

Drill feed rate, run turn-around time and melt water uptake are shown in Figure 2. Overall drilling progress is depicted in Figure 3.

6 - FIELD ITINERARY

The drill team departed Casey on January 11 1988 and arrived at DEO8 four days later after being slowed by a blizzard. Drilling and analysis began on January 17. A depth of 52 metres was reached by January 23 when a bolt and washer came adrift from the drill and lodged in the bottom of the hole. Efforts to drill past these failed (the bolt was retrieved but the washer prevented further passage), and on January 26 a new hole was begun, 2 metres ESE of the blocked one. On February 11 drilling ceased at 234 metres where the ice was deduced from conductivity analysis to be from approximately 1810 AD. The next 3 days were spent measuring borehole temperatures and diameter and breaking out the camp, much of which was deeply buried.

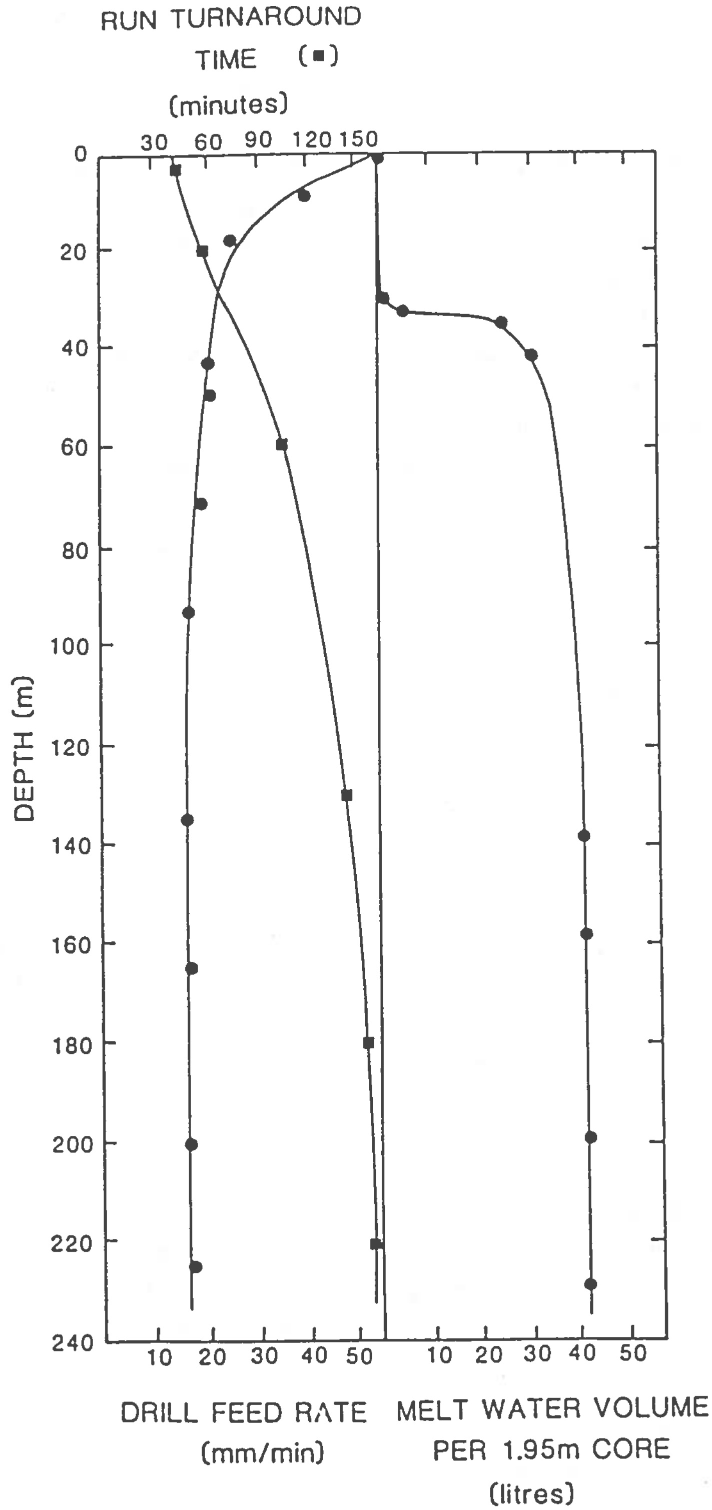


Figure 2 - Drill feed rate, run turn-around time (number of minutes per drilling run for a 1.95 metre core) and meltwater uptake.

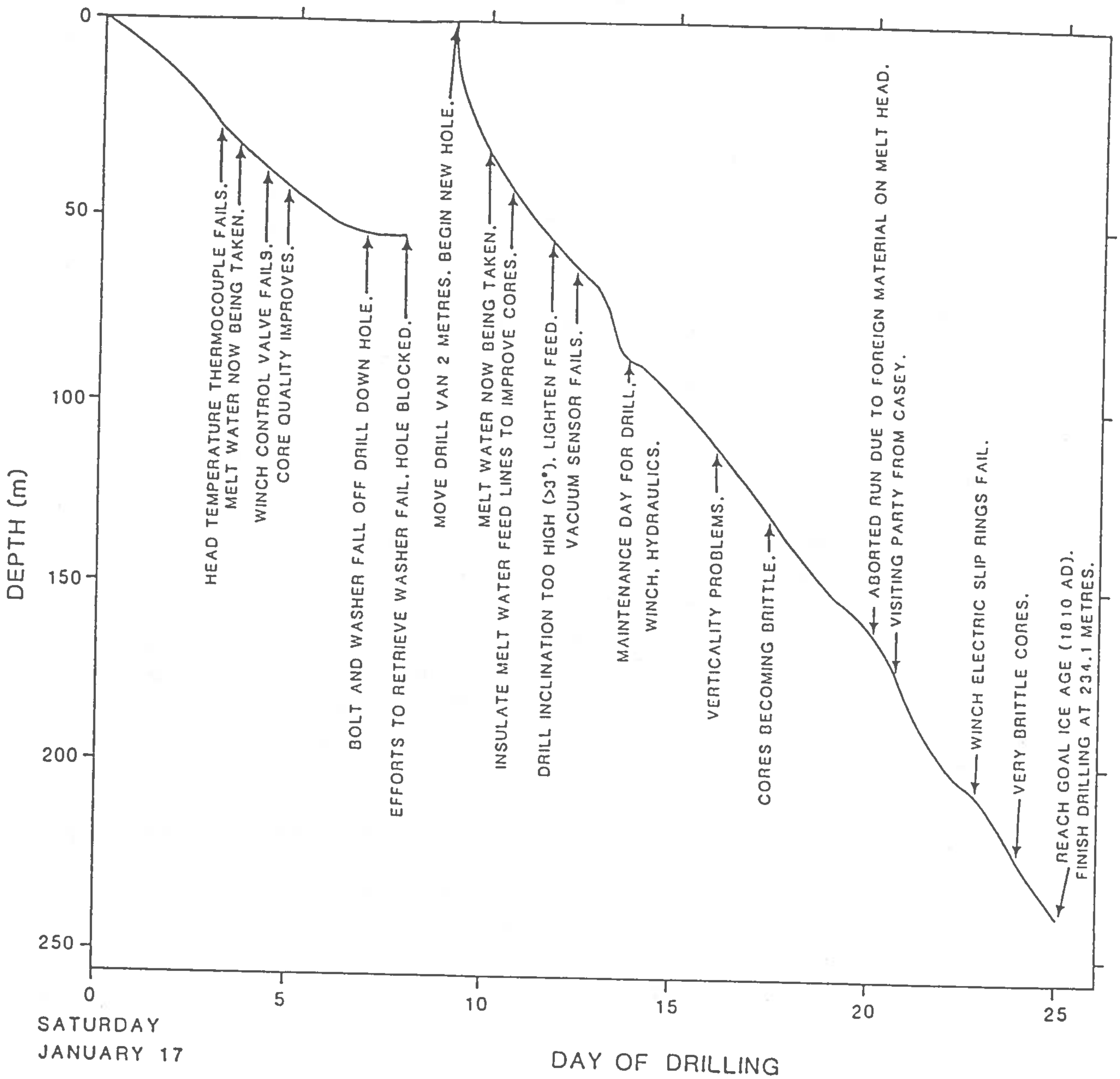


Figure 3 - Drilling progress chart.

7 - CORE DETAILS

Both cores to 52 metres were analysed on-site but only the first was retained, from 20 to 52 metres. The top 20 metres was heavily infiltrated by drill melt water and only samples were retained. The second core was analysed and retained from 52 to 234 metres. The duplication of the top 52 metres of core, although not planned proved very useful to determine the horizontal reproducability of core analysis results. The cores were sealed in plastic bags, labelled, placed inside cardboard tubes and plastic end-caps affixed.

The borehole reached to 234.1 metres and the cumulative core length totalled 233.2 metres. The difference was attributed to losses caused by necking completely through cores from the bottom 20 metres and by pieces being lost from brittle cores.

Core and borehole inclination was typically within 3° of vertical but occasionally this would increase to as much as 8°. The suspected cause was the flexible middle joint of the drill. Lightening the feed (i.e. biasing more drill weight to the cable) easily brought the hole back to vertical, with a small decrease in drilling rate.

Core quality below 20 metres was excellent. Typically, each 2 metre core was retrieved with a full, continuous cross-section and 2-3 horizontal breaks. Cores from 160 metres and deeper required careful handling because they were quite brittle. Storing these for about 10 hours was necessary before analysis. Importantly, excessive core heating by the thermal drill, which can damage the ice core gas and other records (Pearman and others, 1986) was avoided. Typical temperatures of the core immediately after removal from the drill were -14°C at 20 mm in from the core surface and -15°C at the centre.

Natural melt layers were found in the core at 81 metres depth (5 mm thick), 184 metres (3 mm), 188 metres (4 mm) and 204 metres (2.5 mm). Several bands of microfractures - horizontal wafering of the core - were seen at 229 metres and deeper. Many light bands of wind and/or radiation crust were observed throughout the core.

Drilling was terminated when ice from approximately 1810 AD was reached, as calculated from the annual cycles in the DC-conductivity record. This provided a sufficiently long age span for the gas record and included a region containing volcanic fallout from the Tambora (1815 AD) eruption, which was also used as a dating horizon. The age-depth relation is given in Figure 4.

All the retained DEO8 cores were kept at -15°C in a refrigerated container for transport to Casey and Melbourne and finally stored in scoops at a core storage facility at -30°C. The warmest temperature the cores were exposed to was -5°C, but this was for no more than an hour.

8 - DENSITY AND GAS ENCLOSURE

The DEO8 density profile is given in Figure 5(a). The density was found by taking a sample from the centre of the core, machining it into a rod and measuring its dimensions and mass. Using the densities of 795 kg m^{-3} and 830 kg m^{-3} to parameterise bubble close-off as described in Section 2, the air is 40 years younger than the ice and 80 % is trapped over 8 years. This does not include the possible effects of firn impermeability. It is possible that air from as

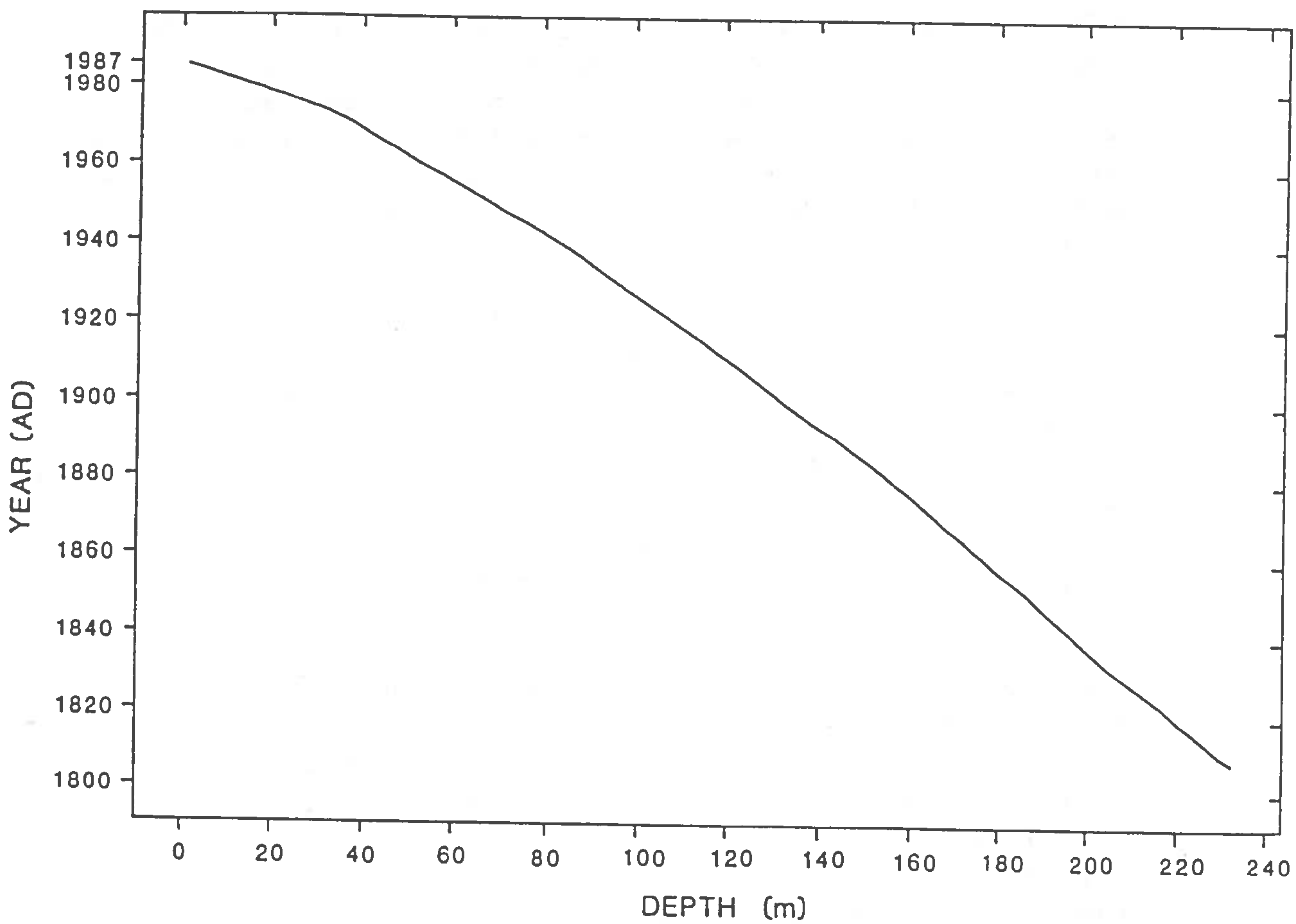


Figure 4 - Age-depth relation for the DEO8 ice core.

recent as the early 1980's is trapped as bubbles in this core.

9 - BOREHOLE TEMPERATURE

The dry borehole was measured for temperature using a Leeds and Northrup 8078 bridge and a cable mounted sensor. A 'Degussa' 100 Ω platinum resistance element was mounted on an insulated arm that could be extended when the instrument was down the hole, forcing the element against the borehole wall. This system ensured good thermal contact and low thermal inertia. About 30 minutes was needed for each measurement. Two sets of measurements were made (see Table 1 and Figure 5(b)). There is evidence that the bottom 30 metres was still slightly disturbed by the heating of the thermal drill, although the remainder of the hole, being drilled more than 2 days prior to temperature measurement, showed no such effects.

10 - SUPPLEMENTARY MEASUREMENTS

A 4 metre deep snow pit was dug about 100 metres south of the borehole and showed only one feature, a 2 mm thick coarse-grained layer. Daily readings of atmospheric pressure, temperature (screen height 1.5 metres) and weather conditions were taken. Surface velocity and bedrock profiles were measured and will be reported elsewhere.

11 - CONCLUSIONS

An ice core from the high accumulation site DEO8 was successfully drilled in 1987. The 195 mm diameter, 234 metre long core should allow accurate analysis of atmospheric greenhouse gases from about 1850 AD to as recent as the early 1980's. The core's high quality, fine age resolution and large diameter will also be ideal for detailed studies of climate, atmospheric chemistry and particles. The drill proved suitable both for intermediate depth core drilling and for drilling a pilot hole to accommodate a casing required for deep electromechanical drilling. The scheme for on-site core analysis and sampling provided useful information during drilling and significantly increased the efficiency of further core analysis back in the laboratory.

ACKNOWLEDGEMENTS

Thanks must go to John Freeman, Peter Mantel and Li Jun for making the DEO8 drilling program successful and enjoyable, to Egon Wehrle for building the drill, and to the personnel of Casey Station for their invaluable assistance.

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Table 1 - Temperature measurements in DEO8 borehole.

Depth	Temperature °C	Hours after drilling measurement was taken
4.0	-18.49	400
12.0	-18.90	420
20.0	-18.98	400
40.1	-19.61	380
55.0	-19.81	400
70.0	-20.05	280
100.1	-20.18	240
130.0	-20.20	190
160.1	-20.25	140
175.0	-20.26	160
190.0	-20.25	90
205.0	-20.25	56
220.2	-20.06	46
220.0	-20.18	58
232.5	-20.30	28
233.4	-20.40	39

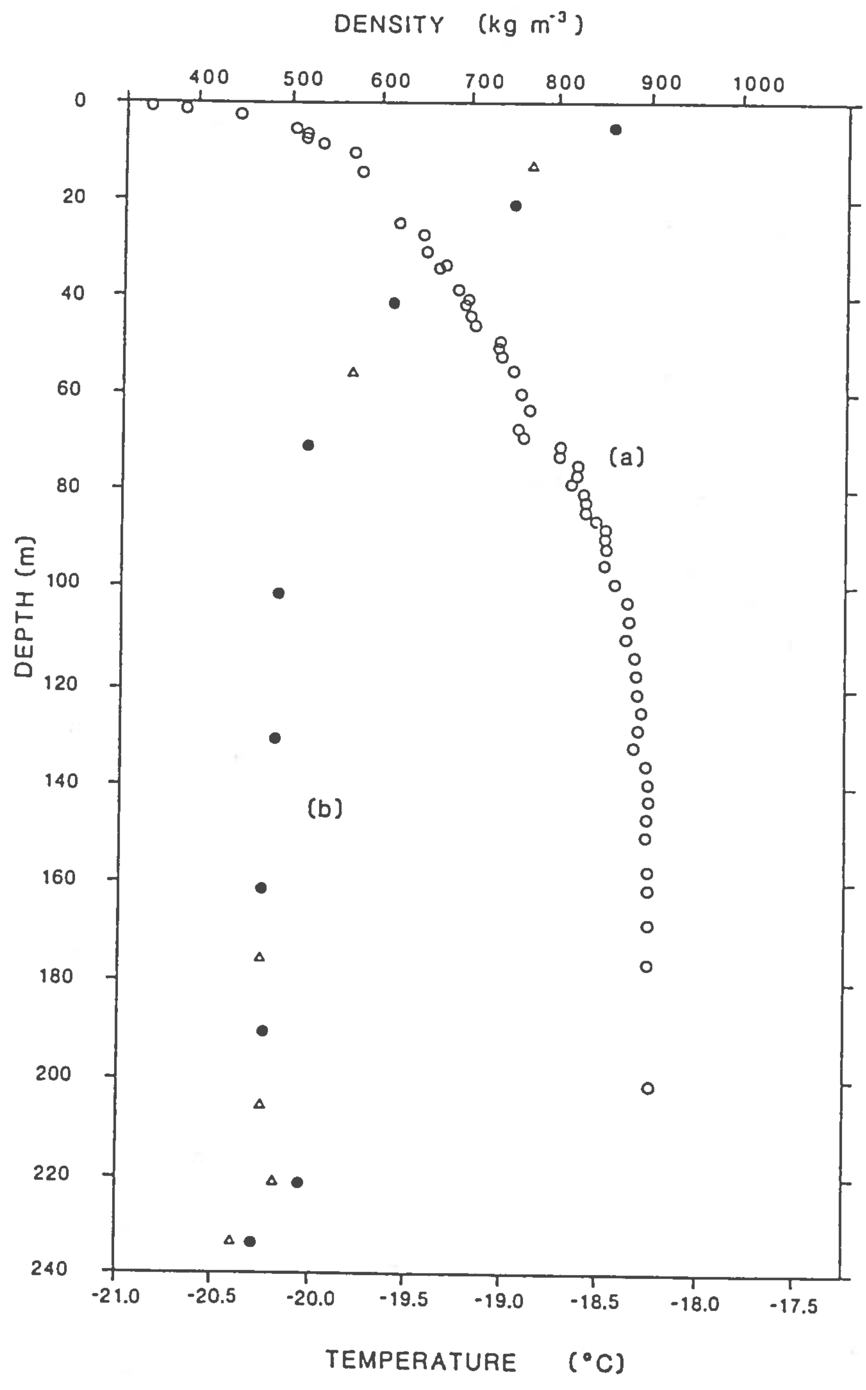


Figure 5 - Profiles of (a) density, and (b) temperature for DEO8.
The solid circles represent the results of the second temperature traverse.

ANTIFREEZE-THERMODRILLING OF CORES IN ARCTIC SHEET GLACIERS

by

V.S. Zagorodnov
Institute of Geography, U.S.S.R. Academy of Sciences
Staromonetny 29, Moscow 109017, U.S.S.R.

ABSTRACT

In 1985-87 two Arctic sheet glaciers : Austfonna (Nordaustland) and Akademia Nauk (Severnaya Zemlya) were cored with an antifreeze electrothermal drill down to their beds at 566.7 m and 761 m depth, respectively. The paper discusses the use of electrothermal drills for studies of the structure and hydrothermal regime of glaciers. It deals both with the equipment and results. The difficulties of drilling are also discussed, as well as ways to cope with them. Experiments on the reduction of bore hole inclination and on drilling of an additional bore hole to obtain an extra core from the bottom glacial stratum are described.

INTRODUCTION

Svalbard and Severnaya Zemlya have mountain-valley glaciers, mountain-sheet glaciers, and sheet glaciers. Depending on the local conditions of climate and topography their surface strata are either composed of firn with ice interlayers, or of consolidated ice. Temperatures of the inner layers range from 0° to -15°C. The melt rates are no less than 100 mm of water per summer. Melt water, with a small amount of sediment penetrates into the glacial body down to several tens of metres, and either freezes there, runs off the glacier over waterproof layers, or percolates down to the bottom via channels. Inside some glaciers and near the bottom there are lenses of liquid water. The hydrothermal situations discussed above can be found in most high-latitude glaciers.

Research on the structure, composition and hydrothermal regime of Arctic glaciers requires drilling equipment that is capable of operating under diverse conditions. Low accessibility of glaciers explains the need for light-weight, low power-consuming, mobile equipment that can be handled by a small team of specialists.

In 1975, the glaciological expedition of the Institute of Geography of the USSR Academy of Sciences began using in Svalbard the electrothermodrills designed at the Arctic and Antarctic Institute by V..A. Morev. These devices, in general, meet the above listed requirements. The thermodrills have been employed to study sheet glaciers with complicated hydrothermal characteristics in the inner layers, located in Svalbard and Severnaya Zemlya /1, 2, 6/.

CHARACTERISTICS OF DRILLING EQUIPMENT

The antifreeze coring electrothermodrill has been described by several glaciological and specialized publications /3, 4, 5, 7/. It has been employed for drilling in Antarctica and in the Arctic. One of the transect bore holes on the Ross Ice Shelf was also made with it. There have been no major changes in the construction of the drill over the last 10 years. The drilling apparatus characteristics are given in Table 1.

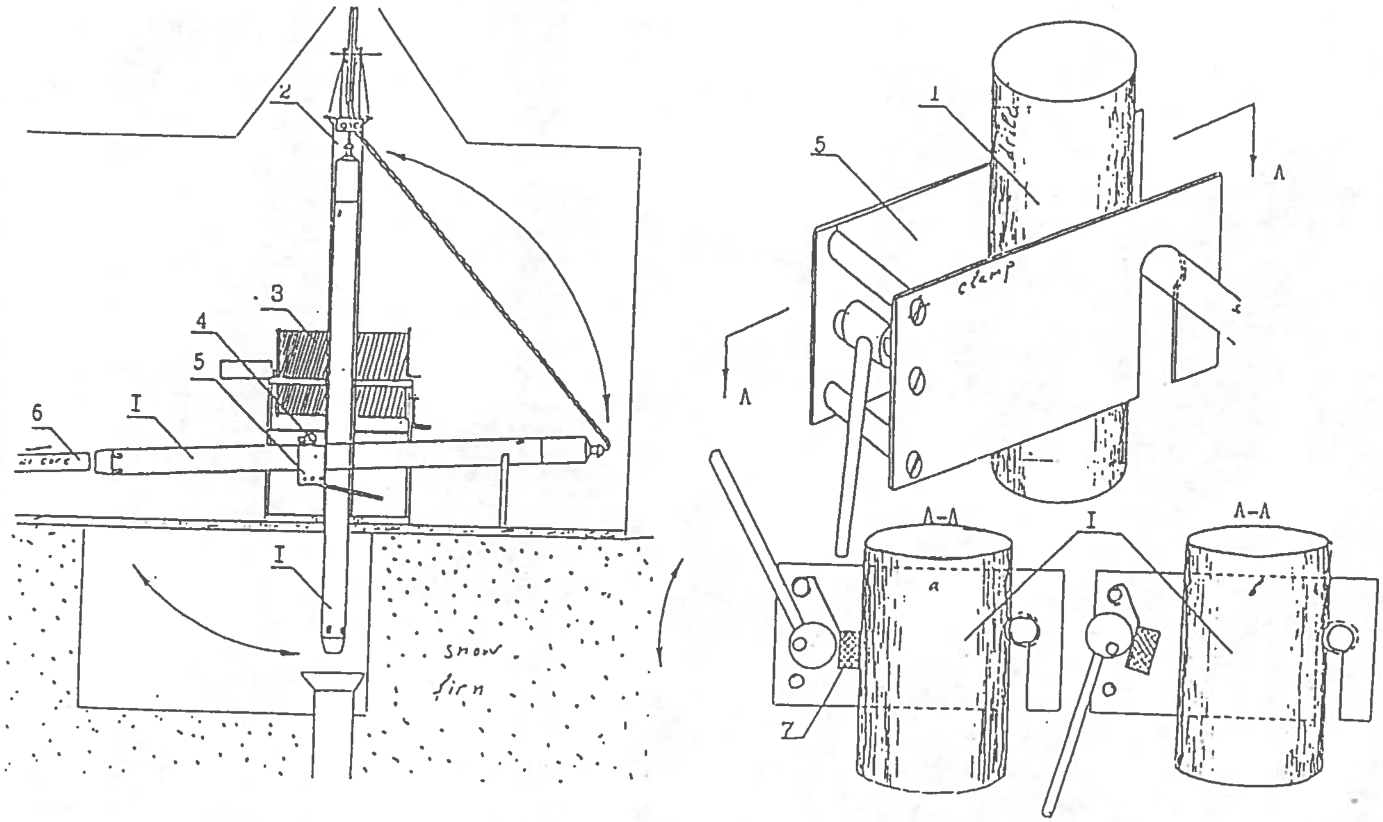
Innovations and improvements have been introduced in the design of a winch and ancillary equipment. The basic parameters of the ancillary equipement are given by Table 2.

To ensure uniform and vertical movement of a thermodrill in the process of drilling-melting, an additional motor-reducer was installed on the winch by changing the voltage of this motor, it is possible to adjust the rates of descent and lifting of the drilling instrument from 0.05 to 36 m per hr. In the process, using this motor, the rate of descent of the thermodrill is kept below the rate of drilling-melting. This ensures vertical movement. On Austfonna the devices were employed for drilling a bore hole down to 566.7 m.

BASIC CHARACTERISTICS OF ANTIFREEZE ELECTROTHERMAL CORE DRILL

Length : drill/core	3.6/2.7 m
Maximum diameter : bore hole/drill/core	118/108/82 mm
Weight : drill/core	75/13 kg
Capacity of heater	2-5 kW
Ice temperature	0° -35°C
Antifreeze	ethyl spirits

Table 1



Arrangement for Re-orientation of Drill in the process of operation. 1 - thermodrill, 2 - mast, 3 - winch, 4 - axis, 5 - fixator, 6 - ice core, 7 - rubber.

Fig. 1

A B C D

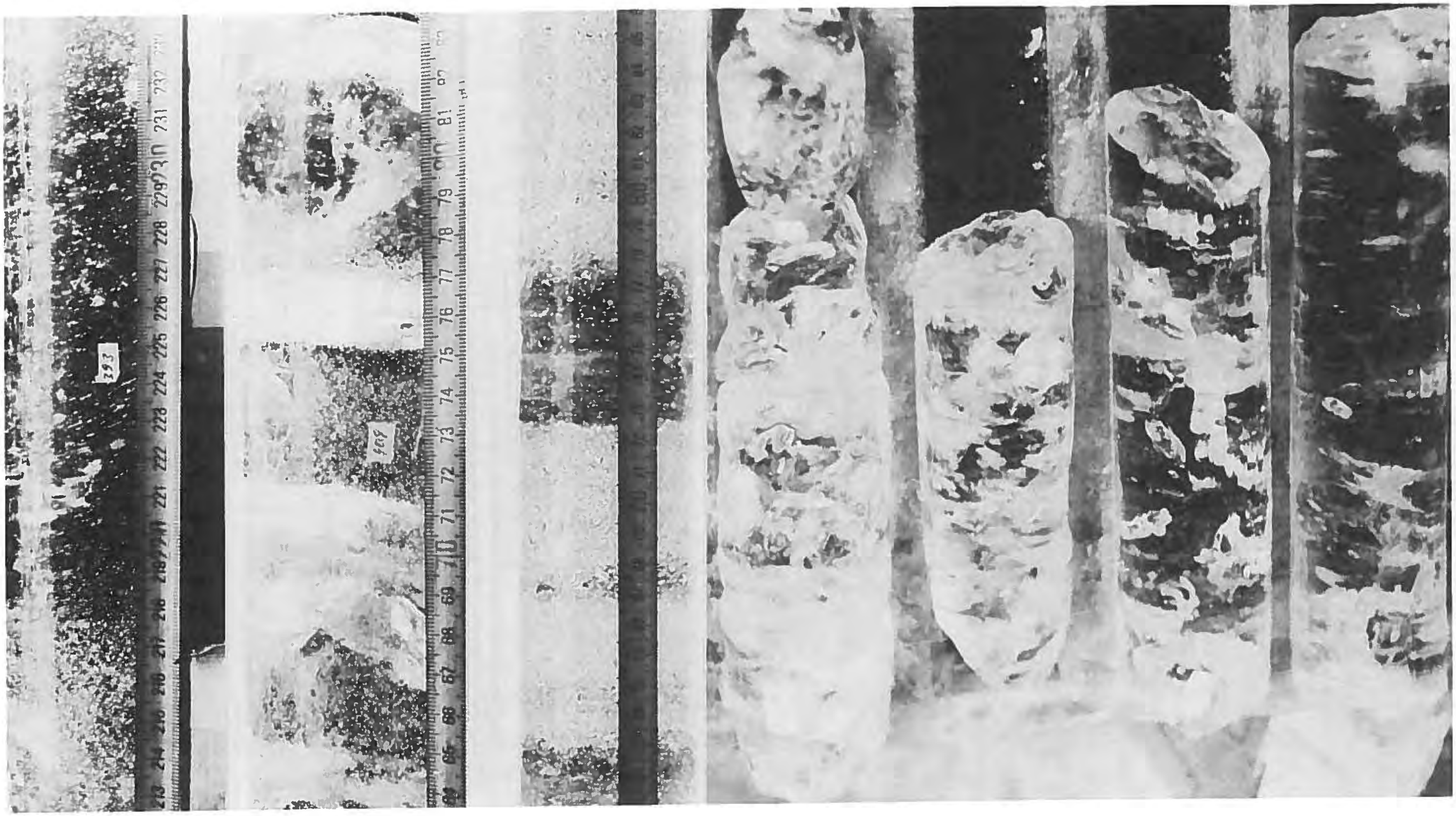


Fig.2 : Fragments of Core
A and B - Akademia Nauk Glacier, depth 477 m and 496 m respectively
C and D - Austfonna Glacier, depth 480 and 566.7 m, respectively.

ANCILLARY EQUIPMENT FOR ANTIFREEZE CORE THERMODRILLING

Dimensions : drilling installation	80 x 80 x 300 cm
control devices	25 x 40 x 150 cm
operational zone	1.8 x 2 + 1 x 1 m
Weight : winch (cable, mast)	500 kg
control devices	150 kg
arrangements	90 kg
Electric power capacity :	
main motor	1.6 kW
supplementary motor	0.15 kW
Rate of descent-lift :	
main motor	1320-2100 m/hr
supplementary motor	0.05-36 m/hr
Cable-line	800 , 8.9 mm, 1 x 2 mm^2 2 layers of steel armour

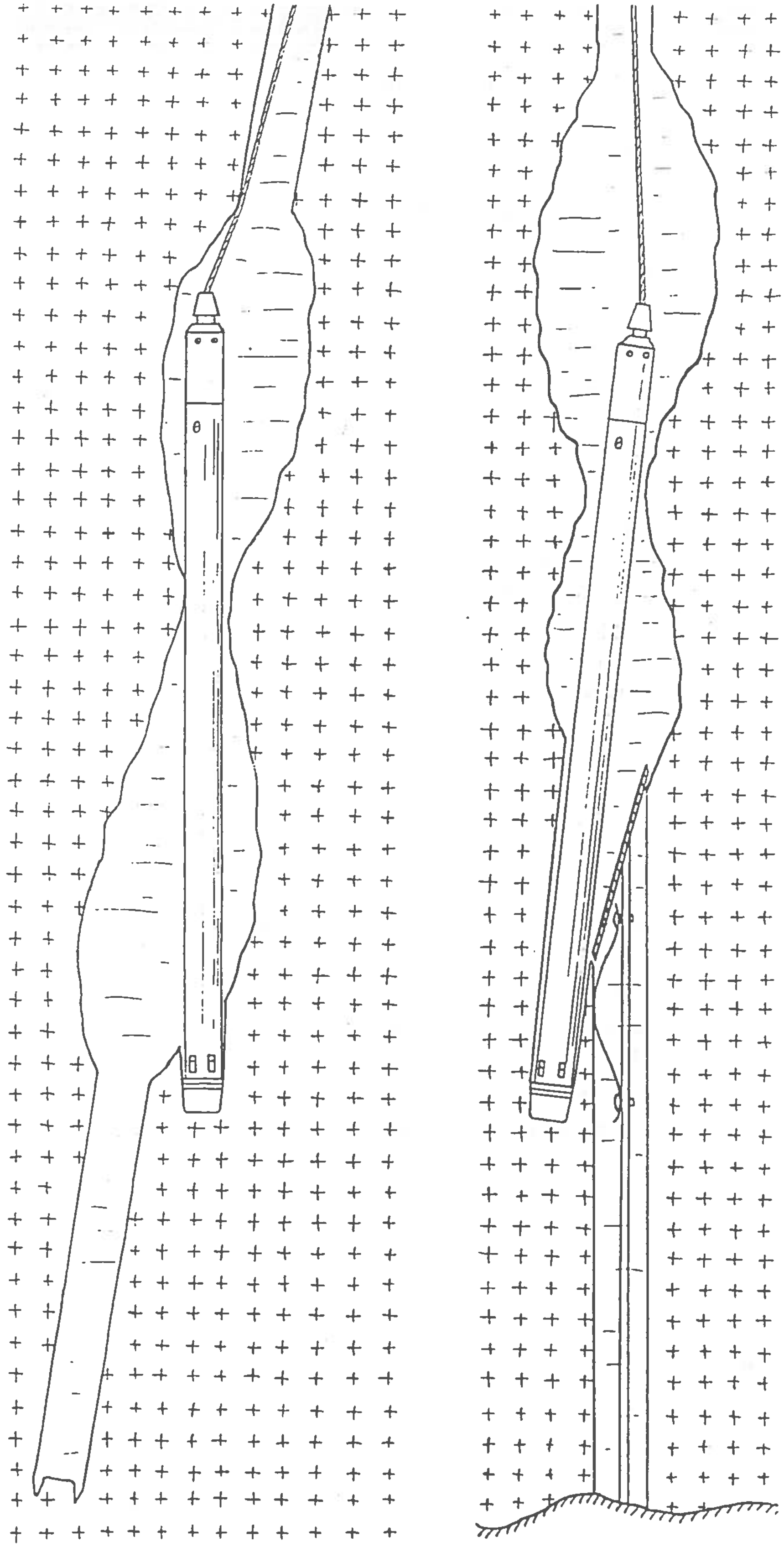
Table 2

To reduce the height of the mast and for more convenient servicing of the drilling instrument, a special apparatus was used to reorientate the drill from the vertical to the horizontal position. This apparatus is shown by Fig. 1. The drill attached to the cable-line is fixed by a special fitting on a turning axle. Upon debraking of the winch, the drill turns around the axle due to action of its own weight. The drill can be put into vertical position with the main motor of winch.

QUALITY OF CORE

The notion of "quality of core" includes the following criteria : homogeneity of the diameter along the core, vertical coring, number, size and form of fractures. As disclosed by the experience of drilling in Antarctica and the Arctic, the geometrical characteristics of cores depends completely on the technology of drilling. Selection of the optimal regimes avoids undesirable shape disturbances. Contact with insoluble admixtures in ice with concentrations over 0.5 gr/cm^2 produces unexpected reduction of the rate of drilling-melting and of the core diameter. The techniques used to eliminatic these problems are described below.

Absence of a scale of criteria of core fracturing persuaded us to employ qualitative parameters. Fig. 2a and b shows the typical fragments of cores from depths over 500 m taken from the above mentioned glaciers. They demonstrate the homogeneity of the shape and the consolidation of cores produced with the antifreeze-thermodrilling technology. The lowest quality core is demonstrated in Fig. 2 c and 2d and is represented by pieces 0.1-0.5 m long. Microfractures up to 3 mm wide are also observed in ice around air bubbles. The depth of technological pollution of the core is, obviously, no more than these microfractures. According to analysis of the core quality, the Arctic cores with high concentrations of air bubbles have more



Scheme of experements on decrease of inclination of the bore hole (A) and drilling a new hole (B).

Fig. 3

fractures and splits. In Antarctic ice, the concentration of air lenses is at least twice as high as in Arctic ice. Therefore, the Antarctic cores produced with the antifreeze-thermodrill have more fractures and splits. Probably, the more air bubbles there are, the more fracturing takes place in cores due to decompression.

As shown by experiments, when the extracted core is less than 1.5-1.7 m long, the number of fractures in it is considerably reduced. Longer cores are obviously fractured by the weight of the drill. This fracturing can probably be reduced by increasing the core diameter. According to experience accumulated in drilling over 3 thousand meters of bore holes in the Arctic glaciers, the technological core losses are one tenth of one percent of the depth of a bore hole, mainly due to core fracturing with decompression and drilling of ice with insoluble admixtures.

BORE HOLE PARAMETERS

Bottlenecks in a bore hole are usually formed because of insufficient concentration of antifreeze in the poured liquid. Two reasons for bottlenecks were found : inflow of meltwater to a bore hole from firn, and negative temperature gradient inside a glacier. In both cases concentration of spirit-water antifreeze in the upper part of a bore hole decreases and ice is formed on its walls. The former reason can be eliminated by shifting drilling to another place, or by installing a tube isolating a bore hole from waterpermeable firn layers ; the latter by withdrawal of antifreeze from the area of temperature fall or by adding more antifreeze. According to practical experience, bore holes filled with spirit-water antifreeze and drilled in glaciers with negative temperature gradients are usable for at least one month for descending-lifting of drilling instruments. The above described techniques do not allow long-time operation of a bore hole without maintenance : adding of antifreeze, redrilling of bottlenecks. If antifreeze is partially pumped out of a bore hole, it can be filled with ice by action of the non-compensated pressure of layers. If the liquid is not withdrawn, a surface slush block formes that is initially dissolved by antifreeze. A bore hole can probably be maintained for a long time with three-component antifreeze : water, glycerine, spirits, with higher specific weight than that of water and spirit-water antifreeze.

Curvature of a bore hole takes place because of regulation of driling pressure in the hole. The tested technique of drilling a vertical bore hole was described earlier. In actual conditions bore holes are usually inclinated. In some cases an inclined bore hole has advantages as compared to a vertical one. For instance, an inclined bore hole allows the orientation of pieces of core facilitating studies of the crystal patterns in ice.

Inclination of the bore hole in the Akademia Nauk glacier reached 25°, which made drilling rather difficult.

To reduce inclination the experiments shown in Fig. 3 were carried out.

First, with a thermodrill, two cone-shaped cavities were produced ; this being done with different regimes of heating, the duration increasing from 1/4 of an hour at the narrow side of the cone to 1.5 hrs at its wider side. The step of movement of a heater is about 1.5 times more than the width of the heater ; the vertical dimension of each cavity is 1/4 more than half a length of a drill. First the upper cavity was prepared, then the lower one. In a second phase, by action of its weight, the drill turns in cavities ; if the rate of its descent is made lower than the rate of drilling-melting then a new bore hole with a lower inclination will be produced. This was done made twice ; in the first case inclination of the new hole was 5° from the initial hole, and in the second case about 15°. Probably, if more time is spent on preparation of cavities, this angle may be increased.

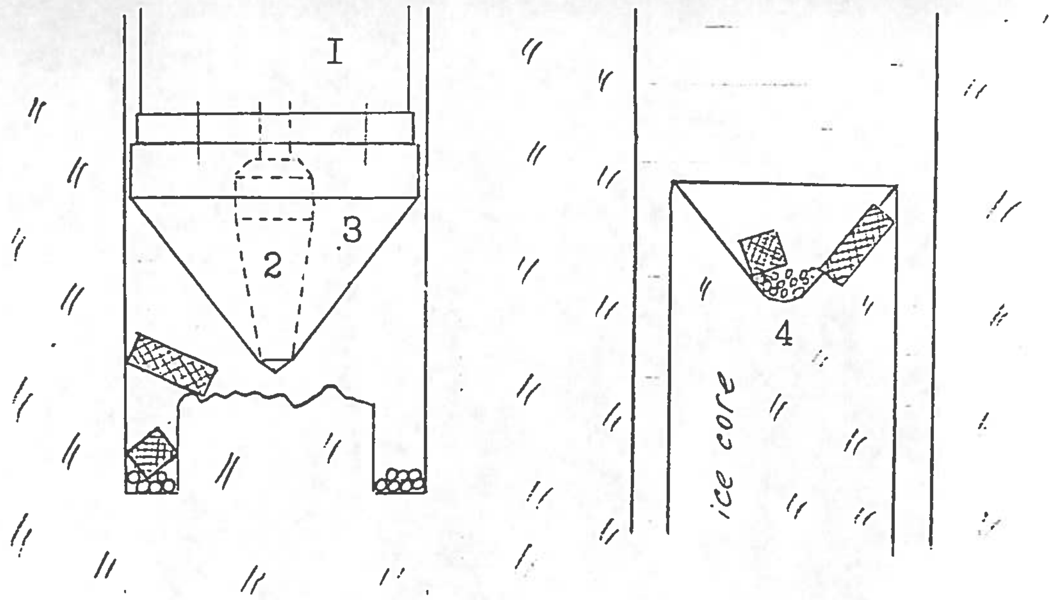
The need to change direction of a vertical bore hole can emerge because of freezing of a drill inside a bore hole, or because it is necessary to take one or several additional cores from the bottom strata of a glacier. Such an experiment, shown in Fig. 3, was implemented after drilling was finished in Austfonna. On the bottom of the bore hole a tube about 5 m long was installed, in its upper part a wedge and a flat spring fixed the apparatus in the bore hole. With the above described technique, 2 cavities were made and one more hole was bored. After the first attempt 1.65 m of core was extracted, and during the second operation the drill was stopped, probably by a wedge, after extraction of 0.95 m of core. The bottom of the second borehole was approximately 1.3 m from the glacier's bed. Other attempts to reach the glacier's bed were not made.

As was already mentioned, when coming across ice strata with 0.5 gr/cm^2 of insoluble admixtures, the rate of drilling-melting decreases 2-4 times and the diameter of the core becomes 50-70 mm. As a rule, dust strata are found near the glacier bottom, but in the process of drilling dirt is gradually accumulated in a bore hole. It is washed from the cable-line and comes with the antifreeze mixture and with meltwater. The above mentioned concentration of technological dirt is accumulated after 100-300 m of drilling, after which the bore hole is cleaned. The technology of evacuating dust, rock debris, nails, and similar items is illustrated by Fig. 4. By a conic heater equal in diameter to the drill, a pit is melted in the bore hole bottom that accumulates undesirable items. With the subsequent drilling, this dirt is extracted out of the bore hole to the surface. In several cases, rock debris up to 2 cm wide was removed from a bore hole. For this operation the core is not lowered by more than 0.3 m.

DRILLING RESULTS

Bore hole drilling in the area of the ice divide of the Akademia Nauk glacier in July-August, 1986, met with some technical and technological difficulties (6). The negative temperature gradient inside the glacier produced slush from antifreeze solution in the bore hole. To cope with this problem the solution was pumped off till depth 160 m. Imperfections of the system of regulation of the drill pressure resulted in inclination of the bore hole ; below depth 360 m the inclination reached 25°. The average rate of drilling for 42 days was 13.3 m per shift. Because of antifreeze shortage drilling was stopped after 561 m of core had been produced. By summer of 1987 the bore hole was partially filled with ice, drilling was continued from depth 220 m at the same rate and 541 m of core was produced. The bore hole reached the bottom of the glacier. At the drilling site the glacier was 720 m thick.

Drilling of a bore hole 1.7 km from the ice divide of Austfonna was started in June 1985 before surface melting. 7 m down, at the boundary of firn and impermeable ice, water lenses were discovered. Firn layers at depths 15 and 30 m drained the drilling solution from the bore hole. Within the depth interval 7-20 m, the temperature of the ice strata is close to the ice melting temperature and downward it decreases. Water running into the bore hole from firn strata was freezing on its walls at rate of about 1 mm/hr. A negative temperature gradient in



WITHDRAWAL OF UNDESIRABLE ITEMS FROM A BORE HOLE.
1 - Core thermodrill ; 2 - Electric heater ; 3 - Metallic cone ; 4 - Ice core.

Fig. 4

the inner layers and the inflow of water from firn produced intensive formation of slush from the solution. These phenomena made it difficult to descend and lift the drilling instrument. Drilling was stopped at depth 204 m (1).

In spring 1987, operations were continued at the same site. In several bore holes it was found that the amount of intraglacial water in the 7 m deep firn strata had increased. The site of deep drilling was therefore moved to the ice divide. A new boring site was set up in 5 days. Operations lasted from 1st to 23 rd of June. At a depth of 566.7 m the drill touched the glacier's bed. Core losses were 0.3 per cent of the depth of the glacier. Except for minor breakages that were repaired without interruption of drilling, there were no major difficulties. The negative temperature gradient inside the glacier down to 165 m caused slush in the bore hole. To dissolve slush blocks, from 5 to 10 litres of spirit antifreeze was added to the bore hole even 4-5 days. Additional use of spirits accounted for no more than 3 % of its total use. In all 1000 litres of ethyl spirit was utilised for drilling in Austfonna. To fill such a bore hole with diesel fuel, five times as much would be required.

The core taken from the bottom strata of the glacier (Fig. 3d) is composed of friction-regelation ice. This ice (Fig. 5) has individual air bubbles up to 1.5 mm in diameter ; around them flat split is formed up to 20 mm wide. Split surfaces have a 30° inclination to the horizon. The major feature of this part of core is the presence of subvertical channels up to 100 mm^2 in diameter. Above the 2,5 m thick layer of this ice, no such channels were found. In the other core such channels were also present.

Four days after reaching the glacier's bottom the level of drilling solution in the bore hole raised from the depth of 80-85 m to about 60 m. The temperature at the glacier's bed measured 6 days after completion of drilling was -1.5°C ; the temperature of the ice melting at the glacier bottom was about --0.42°C. This temperature discrepancy is probably explained by the inflow to the bore hole of mineralized water from beneath the glacier. Three days directly after raising of

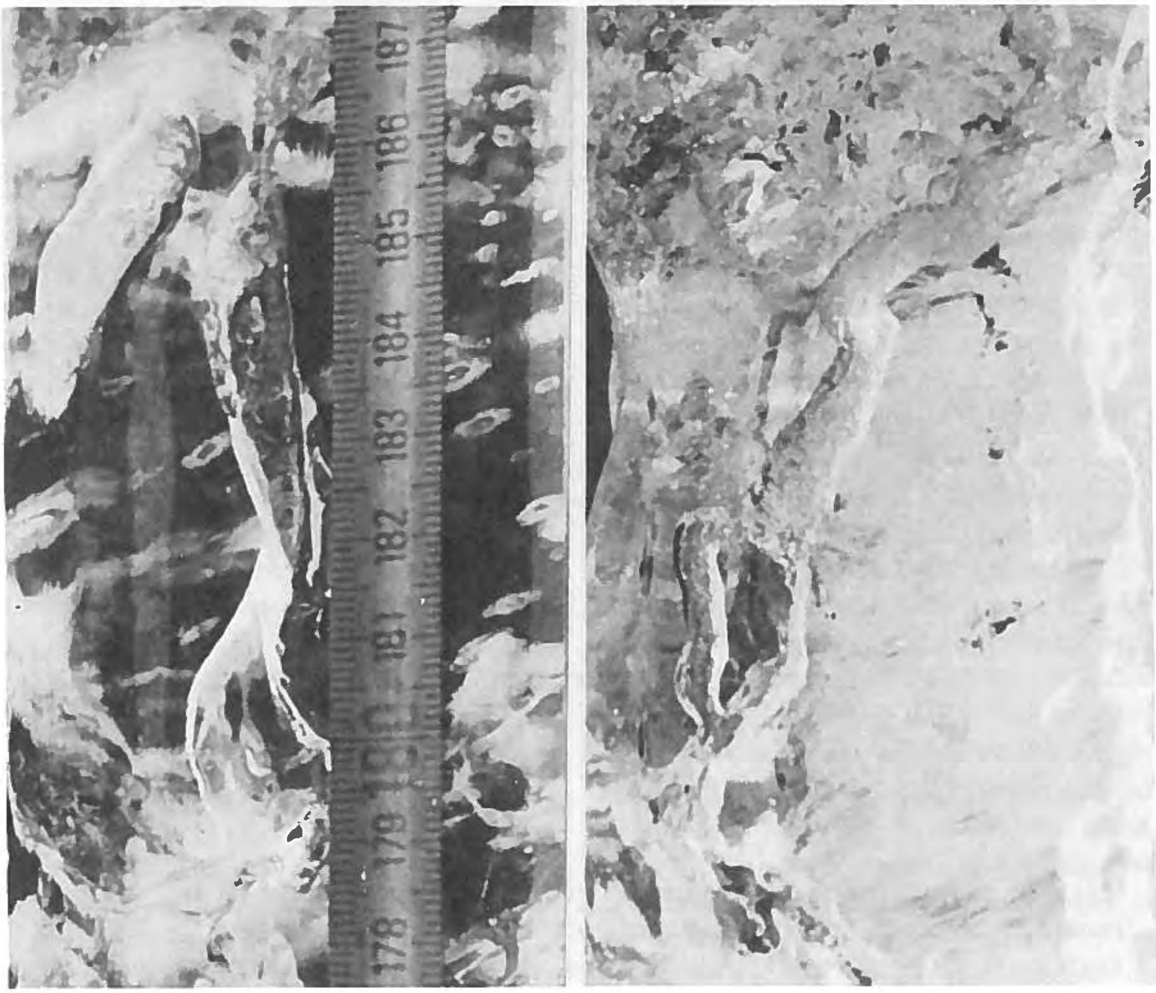
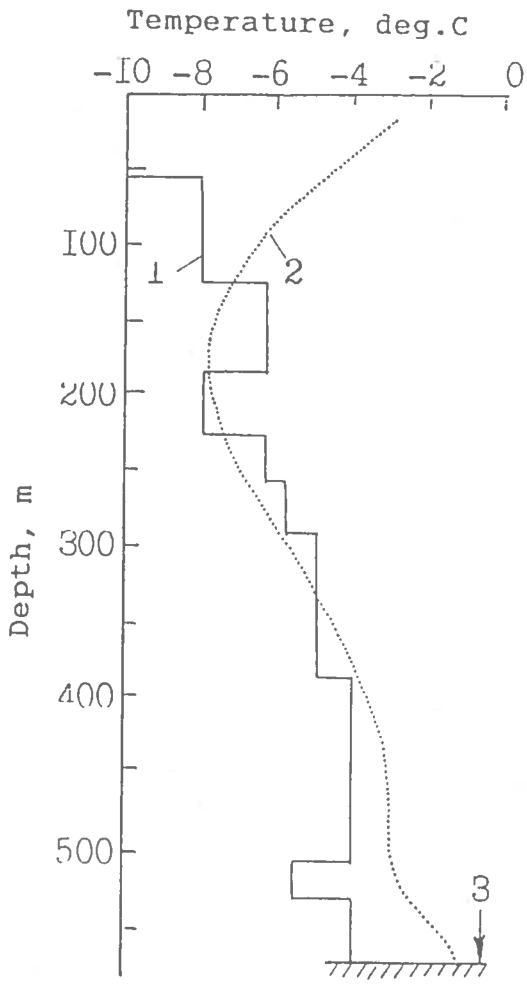


Fig. 5 - Fragments of core with channels from the bottom stratum of Austfonna.

the level of solution in the bore hole, the formation of slush and bottlenecks was not observed.

Fig. 6 shows the measured temperature profile in the glacier and the calculated profile of the freezing temperature of the spirit-water antifreeze in the bore hole. At the depths 150-350 m, spirit concentration in the solution was not sufficient, but in the process of drilling this did not produce significant amounts of slush. Above and below this sector, spirit concentration in the drilling solution was excessive ; this probably promoted levelling of antifreeze concentration in the bore hole. These observations explain why minor disturbances in the technology produce no rapid and irreversible processes causing damage.

Drilling, preparation of the drilling solution, operation of the petrol-electric generator and transportation of the core to the base camp were carried out by 2 persons. Average rates of drilling of this bore hole per shift are shown in Fig. 7. The mean rate of drilling for 12 hours was 25.8 m. The rate of drilling-melting would be increased by 20-30 % with an electric power generator with a capacity 5-6 kW. Use of a more powerful electric motor for a winch would decrease by 20-40 % the time for lifting a drill from a bore hole. Some time could also be saved in the actual drill operation. The above improvements would achieve a mean rate of drilling of 70-80 m for 24 hours when drilling down to 1000 m. However, to reduce fracturing of the core, its length extracted at



Temperature profiles inside the glacier (2), temperatures of freezing of the antifreeze solution in the bore hole (1) and melt point of ice at the bottom (-0.42 deg.C) (3).

Fig. 6

a time should be reduced to 1.5-1.7 m. In this case the mean rate of drilling would be decreased down to 50 m for 24 hrs. The problem of improvement of the quality of core can probably be solved through work on perfecting the drill.

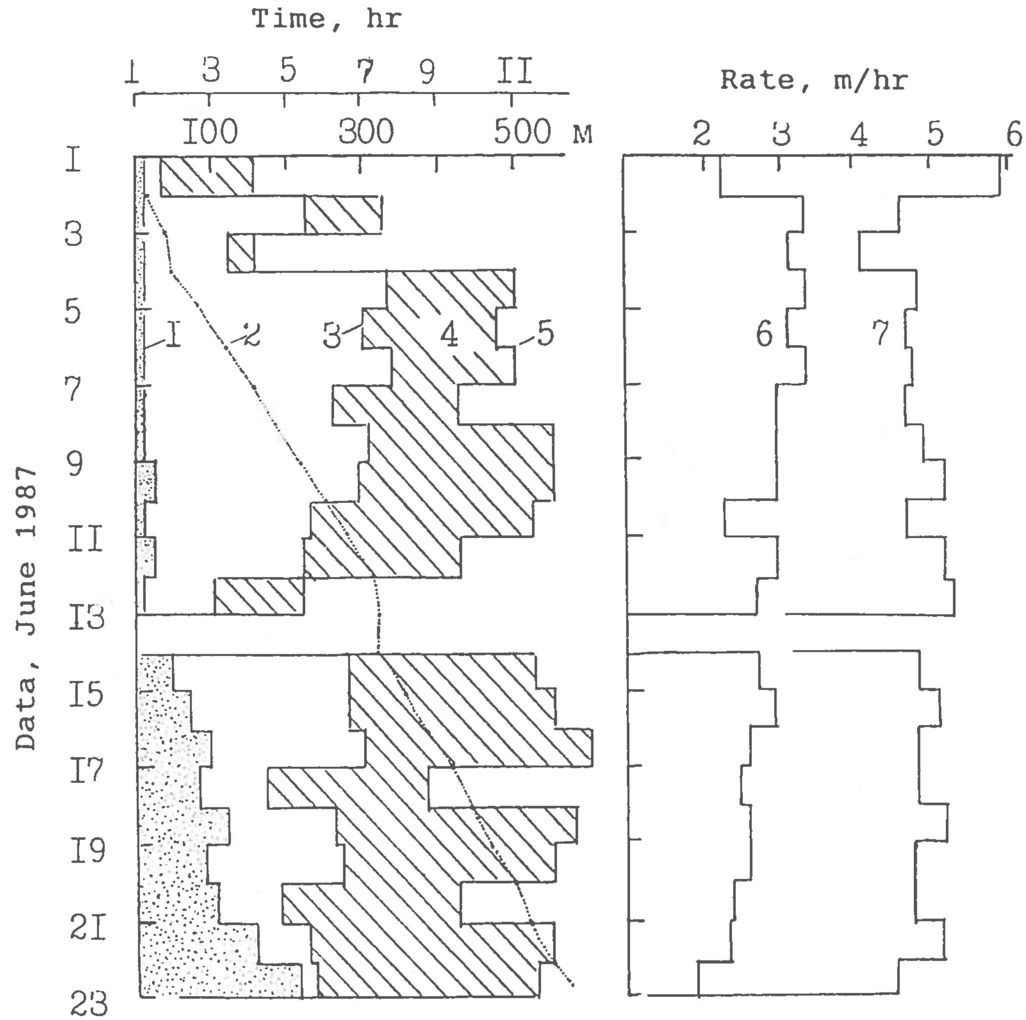
For example, the inside of the core-keeping tube could be re-designed to support the core along its fall length instead of only at the bottom.

CONCLUSIONS

The major advantages of the antifreeze-thermodrilling technology are : low dimensions and weight of equipment, simple and reliable operation, low power consumption, high quality of core. With rather simple techniques it is possible to reorientate a bore hole, thus producing an additional core from the near-bed strata of a glacier.

ACKNOWLEDGEMENTS

Field experiments on the Akademia Nauk glacier in Svernaya Zemlya were made possible by the specialists and equipment provided by the Arctic and Antarctic Institute and Leningrad University. The operation on Austfonna was organised by the Svalbard glaciological expedition of the Institute of Geography of the USSR Academy of Sciences. Cores from the above glaciers were analyzed with equipment from the Institute of Geography. The author is grateful to the many participants of the field experiment who contributed by their efforts to the successful drilling of deep bore holes and the study of ice cores.



Mean daily parameters of drilling. 1 - total time of descent-lift of a drill, 2 - schedule of drilling of bore hole, 3 - time of drilling-melting, 4 - time of gescent-lift and operation of drill apparatus, 5 - time of drilling, 6 - rate of drilling, 7 - rate of drilling-melting.

Fig.7

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DRILLING WITH ETHANOL-BASED ANTIFREEZE IN ANTARCTICA

by

Morev V.A., Manevskiy L.N., Yakovlev V.M. and Zagorodnov V.S.*
Institute of Arctic and Antarctic Research
Leningrad 199226
Beringa 38

*Institute of Geography of the USSR Academy of Sciences
Moscow 109017
Staromonetny 29

An account is given on antifreeze-thermal drilling in Antarctica.

When drilling deep bore holes in glaciers, to compensate the hydrostatic pressure of the glacial strata the antifreeze liquids of the required density are used, such as kerosene with admixtures of density-increasing components and of liquids based on the ethyl spirit (ethanol). Each of the admixed components has its strong and weak points. Kerosene and the density-increasing components (CFCs) are toxic substances not mixing with water or decomposed by air. Use of such admixtures is associated with several technological difficulties.

As for ethanol, it has low viscosity, is diluted by water in any proportions, evaporates at even low temperatures, density of its water solutions is close to that of ice. In case of need, it is possible to introduce into ethanol solutions the components, that are not toxic, to increase density : high-density spirits, glicerine, for example. Such mixtures can be used for drilling glaciers of all types, including shelf glaciers, within the temperatures ranging from 0 to -60°C. As disclosed by long-term observations, the ethanol-based liquids in bore holes under low temperatures are not decomposing or forming ice crystals, produce no significant pollution of ice core, are ecologically safe, comparatively cheap.

Drilling in Antarctica with filling of bore holes with the spirit-water solutions started in 1974 in the marginal part of the ice sheet in the vicinity of the Mirnyi station ; the major components of the drill for the anti-freeze-thermal drilling-melting were tested then. Use of meltwater as a component of the antifreeze solution in the bore hole allowed to do without the facilities for pumping water from the bore hole to the surface. This considerably simplified construction of the drill, made it shorter, reduced weight of the drilling equipment, the volume and weight of the liquid to be pumped into the bore hole, thus facilitating its transportation to the glacier. The design of the drilling equipment, technology of drilling, composition of the liquid pumped into the bore hole are described in (*).

Drilling and exploration of the first bore hole have disclosed, that when filled by ethanol-based antifreeze mixtures, they can be operated for several years, giving rather high-quality ice core suitable for the majority

* Procedings of 2d Ice Core Drilling Technology, Calgary, 1982, by V.A. Morev et a.

of anlytical technologies. In the 1970-es drilling with filling of the bore holes with the ethanol-based solutions was implemented only on the shelf glaciers and the periphery of ice sheet. For this purpose an electrothermal drill was used, operating at temperatures as low as -36°C. Later on this thermodrill was amended to operate in cold ice in the central regions af Antarctica at ice temperatures -57°C. A new thermodrill, and its modification have two cameras with antifreeze. In the process of drilling-melting the drill inserts into the bore hole practically two volume units of antifreeze per one unit of meltwater ; part of liquid with low concentration of antifreeze goes to the drill and is pumped to the surface. Testing of this thermodrill started in 1982. Data on drilling in Antarctica with ethanol-based antifreeze are given by Table I.

Investigations of the accidents have disclosed the following causes of losses of bore holes : failure of the drill, mistakes of operators, infringement of the technology of filling the bore hole with antifreeze liquid (erroneous selection of density of the solution), inadequate information on the structure and thermal regime of the glacier in the region of the bore hole. These causes can be eliminated by preliminary investigation of the ice strata in the region of drilling (drilling of reconnaissance bore hole), adjustment of drill, training of operators, advancement of the devices controlling the regimes of drilling.

A seasonal base at Komsomolskaya station was organised in 1980/81, in the next season a bore hole 800.6 m deep was drilled.

In the process of drilling the bore hole was filled by the spirit-water solution. After temperature and inclination measurements, in February 1982 the bore hole was conserved. In January 1983 drilling of this bore hole was continued. During the 11-month long interruption of activities on drilling, the state of the solution filling the bore hole was not changed, and drilling went on without complications. When the bore hole reached the depth of 870 m the drill was frozen in the hole because of a wire failure inside the drill. An effort was made to pull the drill out of the bore hole, but the cable broke close to the surface. 870 m long stretch of the cable stayed inside the bore hole at depth of 110 m. Thus, the testing of a new modification of the antifreeze-thermal drill and of the technology of filling a deep bore hole in ice with temperature -53°C gives a solid proof of the possibility to use the ethanol-based filling liquids for long-term conservation of the bore holes in the glaciers with downward increase of temperatures.

Results of testing of the electrothermal drill ETB-5 provided the basis for drilling a new bore hole in Central Antarctica. The site for a new bore hole was selected in a little-known region of Eastern Antarctica in the area of B-dome 77°04 S L, 95°55 E L ; the camp site was conventionally named "Dome B". This is one of the most elevated regions of the continent, the camp being at 3850 m a.s.l. The glacier is underlain by lakes, its surface ice strata move at rates about 0.1 m/year. During several summer seasons the preparatory activities were carried out on the Dome B : assembling of a power-generating station, of drilling facilities, housing. Now the camp can accommodate 6-8 specialists to work during the summer seasons.

Drilling of a deep bore hole was started at the station Dome B in the summer season of 1986/87. In the first phase drilling was done by a special drill ETB-130 (diameter 130 mm) that pumps melt-water from the bore hole. During the first season 780 m were drilled. After temperature measurements the bore hole was filled by ethanol-based antifreeze solution and conserved. In the coming summer seasons drilling would be continued first with the thermal drill ETB-5, and after reaching ice strata with temperatures above -36°C with the thermal drill ETB-3 ; diameter of the two latter drills is 108 mm. Increase of the bore hole diameter in its upper portion will speed up sinking-lifting of the drilling equipment in the coldest horizons of the bore hole, where viscosity of the solution used for filling the bore hole is minimal.

Now the experts on ice drilling are facing the problem of drilling a bore hole that descends into a sub-glacial lake, and of its conservation in the state that would allow for explorations later.

Table I - Basic Data on the Bore Holes Drilled in Antarctica with Antifreeze-Thermal Technology

Year	Site of drilling bore hole depth	Character of ice strata	Observations in the bore hole	State of the bore hole
1975	Lazarev Shelf Glacier, 374 m, down to the ground	firn 6 m	temperature, 5 months	sludge in the interval of negative temperature gradient
1975	the same, 356 m, the bore hole reached the sea	firn 6 m	temperature, oceanology, ground	sea water ascended 4 m, sludge was formed in the lower part
1976	the same, 412 m, the bore hole reached the sea	ice	temperature	the same, the lower 10 m blocked by sludge
1977	edge of glacier,region of Novolazarevskaya station, 812 m	firn 62 m	temperature	the drill is frozen, the cable torn off
1978	Sheklton Shelf Glacier, 202 m, the bore hole reached the sea	firn 62 m	temperature, oceanology	sea water in the lower portion, in 24 hrs a sludge block was formed
1978	Ross Shelf Glacier, the camp -9, 416 m, the bore hole reached the sea	firn 50 m	temperature	sea water in the lower part, the solution ascended 20 m ; sludge is probable in the lower part.
1979	edge of glacier in the vicinity of the Mirnyi station, m	firn 50 m	temerature	formation of sludge in the interval of negative temperature gradient
1982 - 1983	Komsomolskaya station, 870 m	snow-firn 120 m	temperature	conserved for 11 months, the drill was frozen
1988	Dome B, 780 m	snow-firn 120 m	temperature	filled with spirit-water antifreeze, conserved

HOT WATER DRILLING

EVALUATION OF HOT WATER DRILLS

by

K.-H. Bässler and H. Miller
Alfred-Wegener-Institute for Polar and Marine Research.
Bremerhaven, FRG.

1 - ABSTRACT

Caused by the increasing geophysical and glaciological field investigations in polar regions more and more drill holes in cold firn and ice are required. Using hot water drilling a fast drill hole production is possible. Existing evaluations for hot water drills were derived from drill tests in temperate ice for small hole diameters (Iken et al, 1977 ; Taylor, 1984). The present paper shows a possibility, based on thermal calculations in ground engineering to evaluate the necessary heat and the drill rate dependent on

- the hole diameter,
- the firn (ice) density,
- the in-situ temperature of the firn (ice),
- the water flux,
- the water temperature.

For quick estimates some graphs for fixed hole diameters are given.

2 - INTRODUCTION

For some time past the use of hot water drills for the hole production in firn and ice exhibits an increasing trend. For field investigations without the necessity of ice cores this technique offers crucial advantages compared with electromechanical drills :

- a multiplication of the drill speed,
- penetration of ice shelves and ice layers mixed with sediments,
- little susceptibility to mechanical defects,
- the possibility for the recovery of stuck drills.

In the framework of the German Antarctic research Engelhardt et al, 1987 tested a hot water drill on the Ekstroem - and Filchner/Ronne Ice Shelf, which was developed from the University of Münster in co-operation with H. Rufli. In spite of bad weather conditions and technical problems with the winch they were successful in the penetration of both ice shelves in depths of 208 m and 460 m. Reaming of the holes from 5 cm to 10 cm for the installation of a thermistorchain was not possible. Because of the difficulties in reaming holes, caused by the deviation of the nozzle in the pre-drilled hole, the direct production of holes with greater diameters should be considered.

Therefore a model based on thermal calculations in ground freezing was derived which allows the evaluation of the heat and the resulting drill rates dependent on the density, the ice temperature, the water flux and - temperature for various hole diameters. Handy graphs enable quick estimates.

3 - BASIC EQUATIONS

Iken et al, 1977 and Taylor, 1984 defined relations for the determination of drill rates based on drill tests in temperate glaciers and on laboratory tests. In consideration of the flow conditions in the hose, which are decisive influenced by the shape of the nozzle and the efficiency of the hose insulation, they calculated the cooling of the water between input and output, the necessary latent heat and the drill rate. Both neglect the heat, which warms up the unmelted region around the hole.

The aim of the following analysis is the evaluation of the dissipated heat subjected to the firn density, firn temperature and the planed hole diameter. Assuming a linear relation between the dissipated heat and the waterflux at the nozzle warmed up to the temperature T1, the drill rate can be evaluated.

The equations, based on a modell of Sanger et al, 1979 describe the frost propagation around a freeze pipe in hydrous soils. Brine with a temperature of -20°C to -40°C flow through a double walled tube, installed in a hole. After the cooling of the soil further heat extraction leads to the freezing of the pore water and to the building of a frozen solid body. For the assignment of the heat extraction in the case of freeze pipes to the heat supply and the melting of ice the equations of Sanger et al, 1979 were taken over.

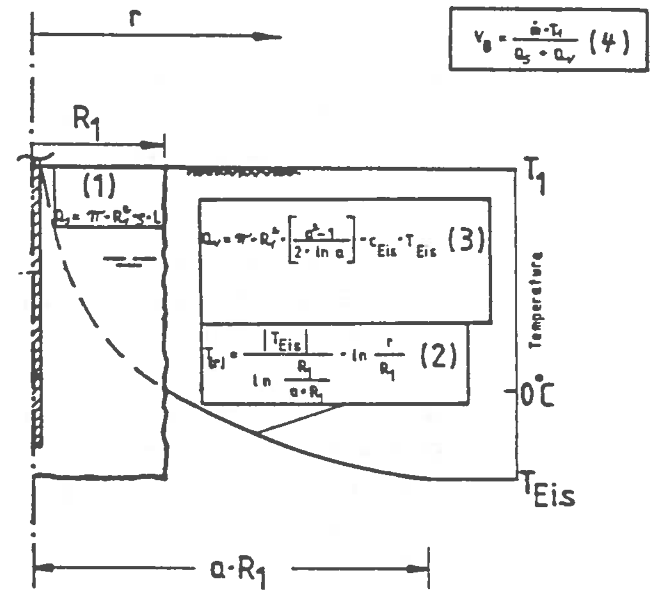

Fig. 1 - Simplified temperature regime around a nozzle during drilling.

In our model the freeze pipe is substituted for the hose. The ice corresponds to the frozen ground. Just as in frozen ground there is a change of the temperature field in the ice around the hole, which needs extra heat beside the latent heat. The cooling of the water in the hole and the occuring convection between water output and top of the hole are not under consideration. The following kinds of heat are considered.

- In connection with the hole diameter and the density of the firn the latent heat of melting Qs can be calculated according to equation (1) in fig. 1.

- Because of the melting of the hole there is a change of the temperature field in the ice between 0°C on the wall and the initial ice temperature in a finite distance from the wall.

Sanger et al, 1979 determined the threefold radius around the hole as the influenced region. Using equation (2) in fig. 1 for the description of the temperature-field the heat Qv needed for the warm up is evaluated according to equation (3) in fig. 1. With the total heat (Qs + Qv) related to the waterflux m with the temperature T1 the drill rate can be calculated using equation (4) in fig. 1.

4 - COMPARISON BETWEEN MEASURED AND CALCULATED DRILL RATES

Taylor, 1984 conducted drill tests in temperated ice and plotted the measured drill rates as a function of waterflux and temperature. There is a good agreement between the measured and with equation (4) calculated values (see fig. 2).

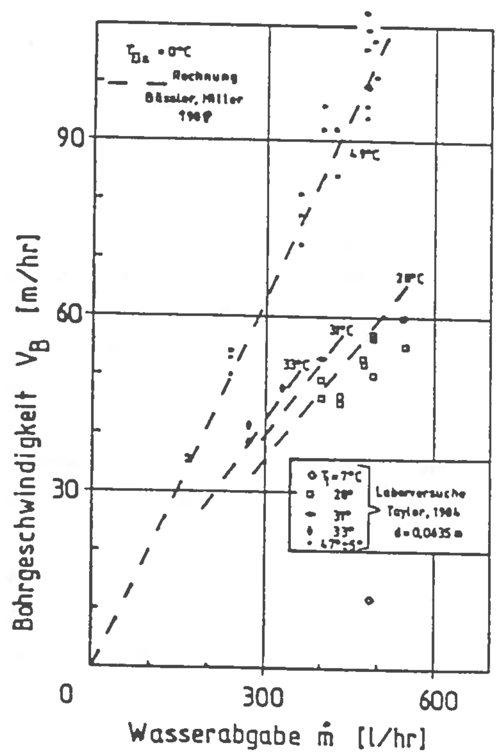

Fig. 2 - Comparison between measured and calculated drill rates.

It should be noted that Taylor's relations for the determination of the drill rates coincide with the doted lines, the plot of equation (4) in fig. 2 because of the fact that the ice temperature during the tests remained at 0°C and only the part describing the latent heat is needed.

To compare equation (4) including the heat Qv and the density relation a reported hot water drilling on the Ross Ice Shelf will be used.

Koci, 1984 describes the use of the Browning Hot Water Drill at J9 where a hole with a diameter of 76 cm was drilled with an average drill rate of 42 m/hr down to 420 m in depth. The waterflux was 19 200 l/hr with a temperature of 98°C on the surface. An average temperature decrease of 3.3°C/100 m was recorded. A linear evaluation of the down hole temperature T1 resulted in

$$T1 = 98 - (4.2*3.3)/2 = 91°C.$$

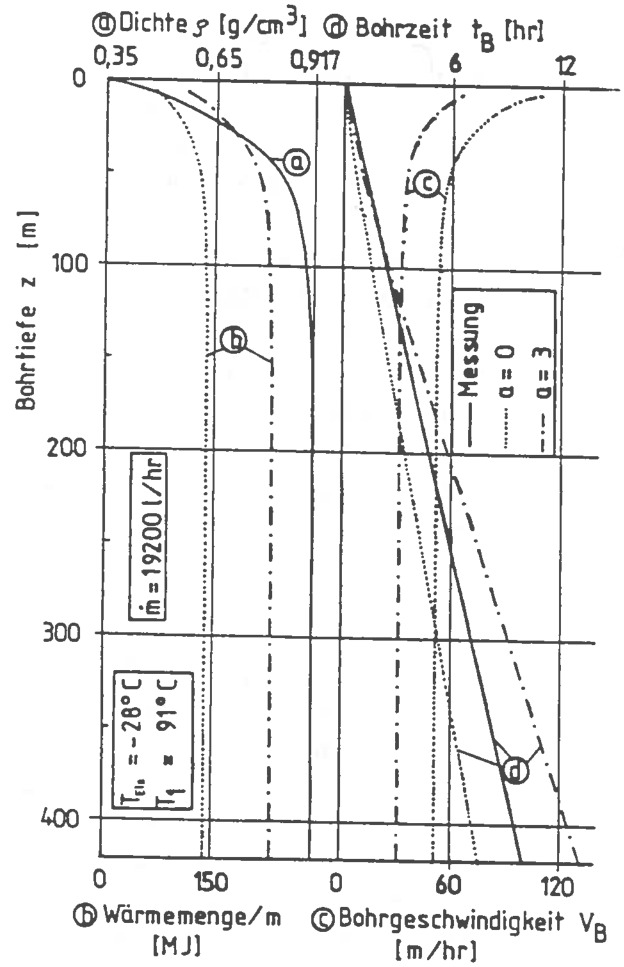

Fig. 3 - Calculated heat, drill rate and drill duration for a hole on the Ross Ice Shelf.

The in-situ ice temperature amounted to -28°C. Related to a depht-density profile for the Ross Ice Shelf near Little America V (Bender et al, 1960) the heat, drill rate and - duration for separated layers were calculated and plotted as a function of depth (fig. 3). The calculations were made for two cases. In the first case only the latent heat was considered (doted lines) and therefore smaller values were calculated compared with the reported average drill duration.

Using a value of a = 3 to describe the zone of temperature influence and an average ice temperature of -28°C the duration is higher maybe because of the neglect of the increasing temperature in the lower part of the ice shelf.

5 - DIAGRAMS FOR CALCULATION OF HEAT AND DRILL RATES

In fig. 4a - 4c diagrams for three hole diameters (0.1 m, 0.3 m, 0.6 m) are shown to evaluate the necessary heat according to firn density and temperature. With a waterflux of 1000 l/hr it is possible to estimate the drill rate using the lower part of the diagrams dependent on three different watertemperatures.

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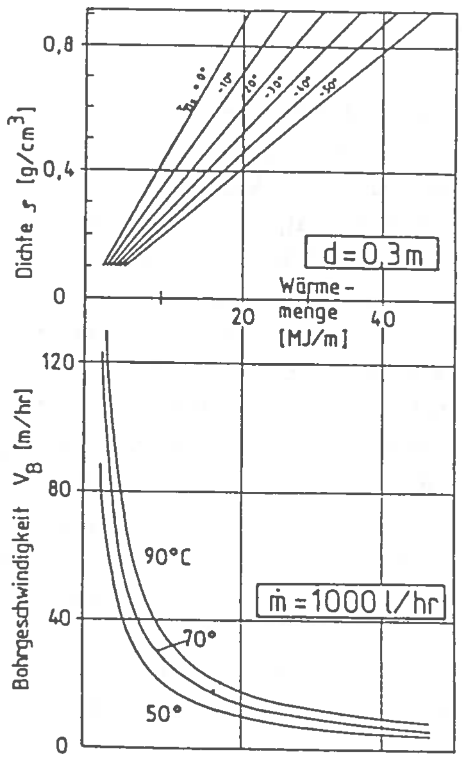
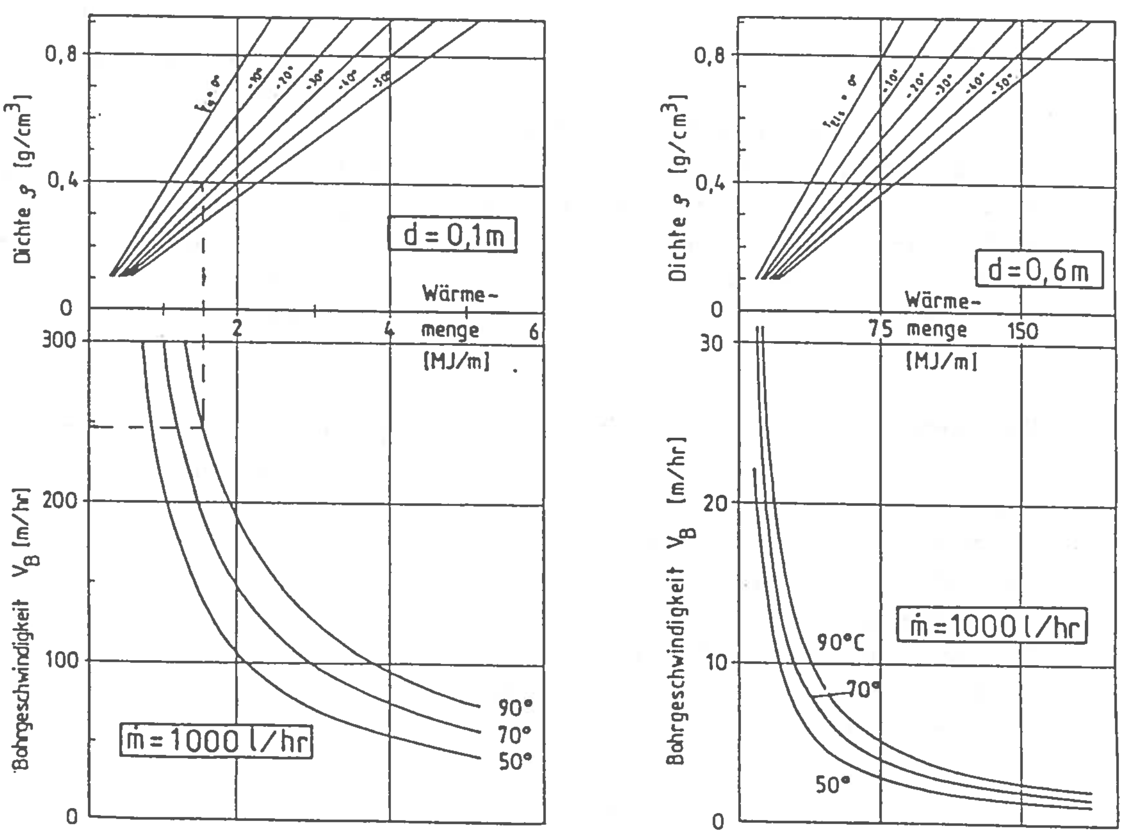
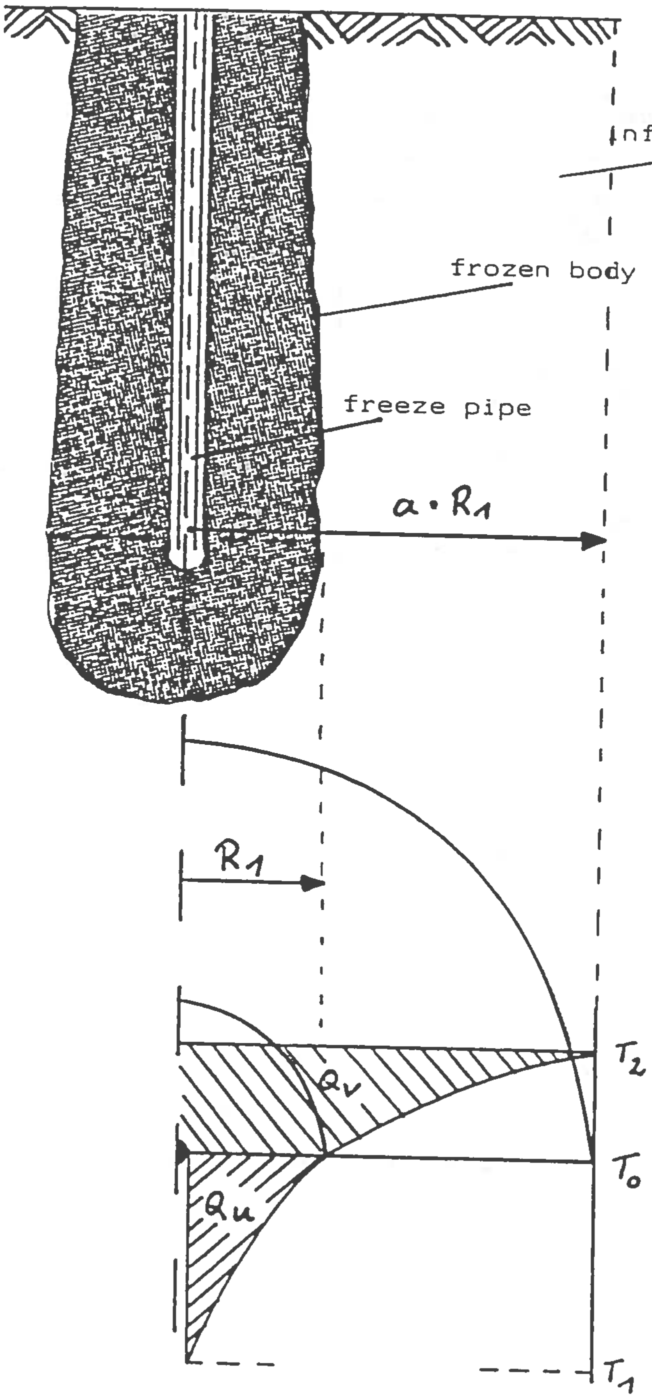


Fig. 4a-c - Diagrams for the estimation of heat and drill rate.

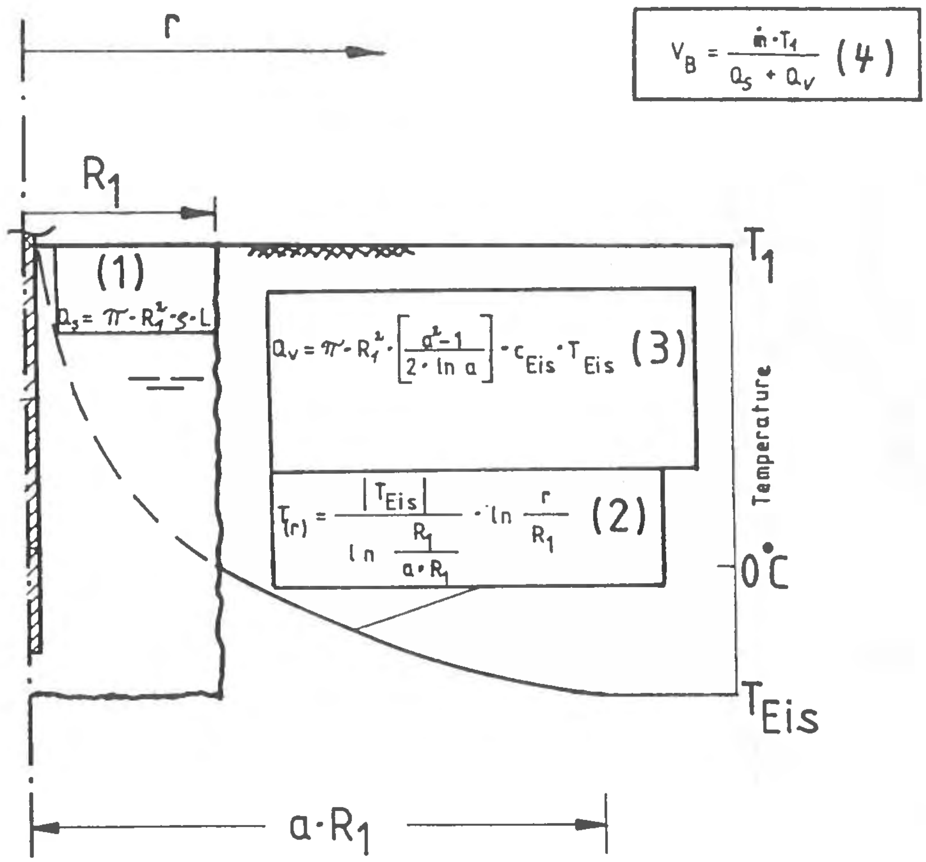


<u>Engineering model used in ground freezing</u>



R_1	radius of frozen zone
a	ratio between frozen and influenced region
T_0	freezing temperature of the ground
T_1	pipe wall temperature
T_2	initial temperature of the ground
Q_s	latent heat of melting
Q_v	heat needed to cool down the influencend region before freezing
Q_u	heat needed to cool down the frozen region

Transfer to hot water drilling



R_1	radius of melted hole
a	ratio between melted and influenced region
T_1	water temperature
T_{Eis}	initial ice temperature
Q_S	latent heat of melting
Q_V	heat needed to warm up the influencend region before melting
Q_u	heat needed to warm up the water in the hole after melting (neglected)
$\dot{m}$	water flow rate
V_B	drill rate
	firn density
C_{Eis}	heat capacity of ice

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

by

A. Iken, K. Echelmeyer, W. Harrison
VAW, ETH-Zürich and Geophysical Institute,
University of Alaska

ABSTRACT

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

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

INTRODUCTION

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

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

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

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

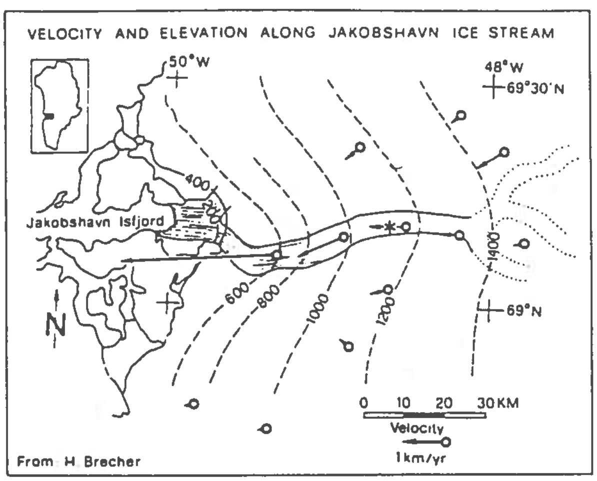


Fig. 1 - Jakobshavns Glacier. The location of the drill site is indicated by an asterix.

REQUIREMENTS FOR DRILLING TO LARGE DEPTH

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

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

where

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

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

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

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

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

where

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

= $7.15 \times 10^{-5} m^2 \; kWh^{-2/3}$

d = nozzle diameter (m)

H_v = latent heat of ice (per unit volume)

c_i = heat capacity of ice (per unit volume)

ϑ_i = ice temperature (°C)

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

CHOICE OF EQUIPMENT

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

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

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

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

where

μ is the coefficient of friction between hose and wheel

$\alpha = 45°$ is the angle of the groove.

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

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

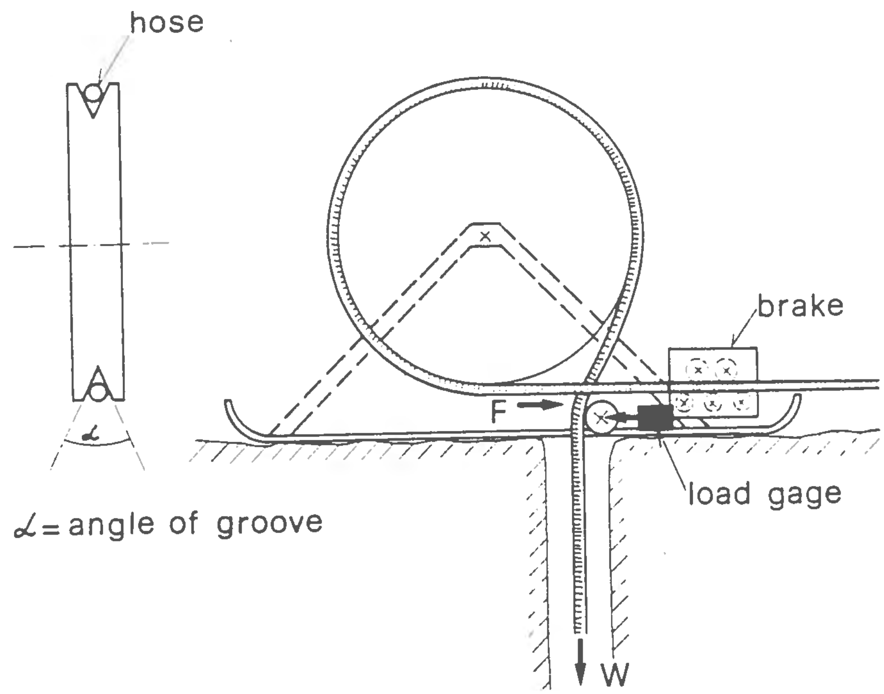


Fig. 2 - Scheme of winch.

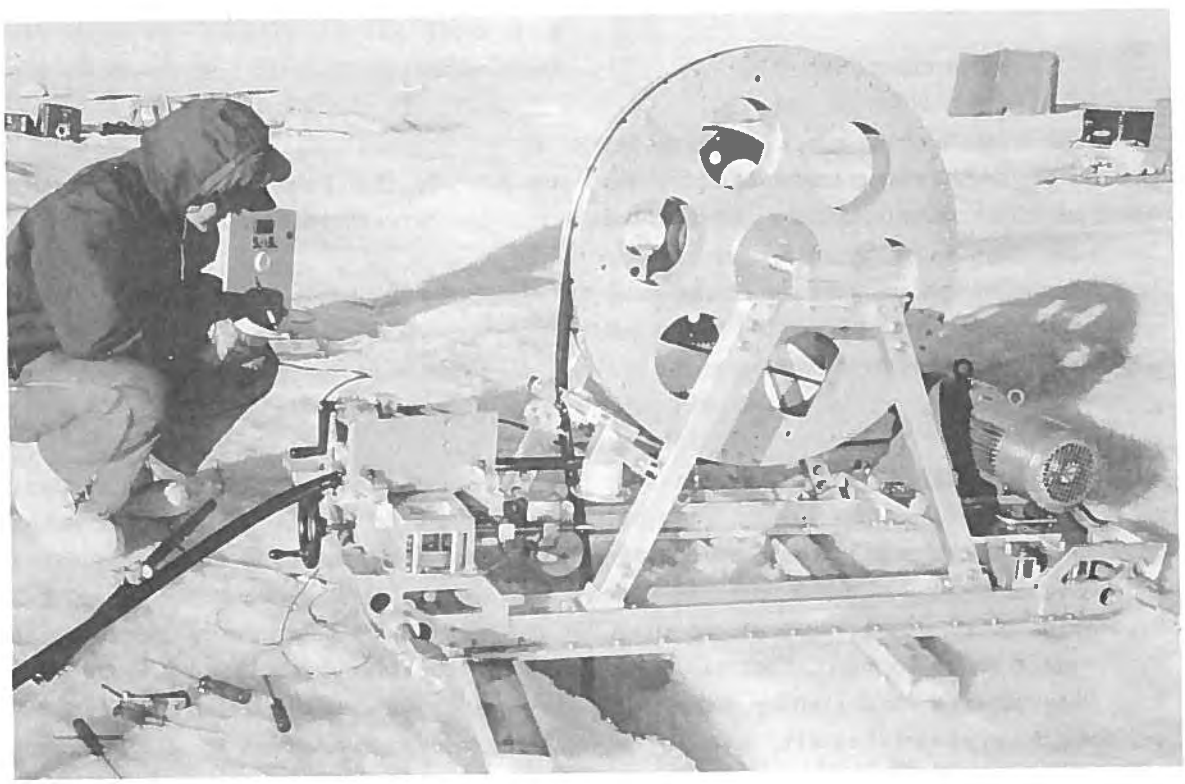


Fig. 3 - The winch during operation (photo taken by P. Gnos).

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

CONTROL OF DRILL SPEED AND HOLE SIZE

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

Graphs similar to Fig. 5 were used for adjusting the drill speed as the depth of the borehole increased. For example : if a borehole with twice the cross-section of the test hole is to be drilled, the drill speed is set to half the speed used in the test run ; this case is indicated by line 4 in Fig. 5. Maximum drill speeds obtained using different water temperatures or discharges are depicted by lines 1 and 3, respectively. These examples refer to a nozzle with 4 mm diameter. Alternatively, line 1 can be interpreted as the maximum drill speed at ϑ_0 = 50°C, Q = 3.6 m^3/h and a nozzle diameter of

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

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

RECORDS OF APPLIED PRESSURE

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

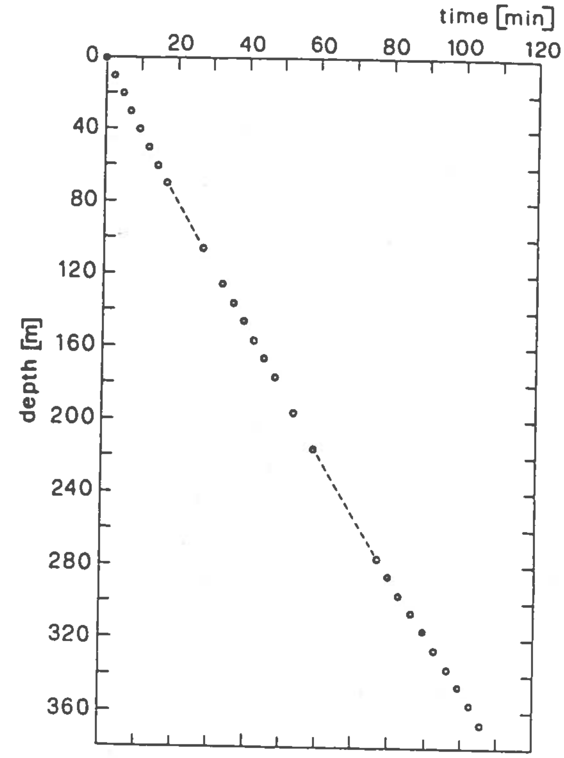


Fig. 4 - Depth of drill as a function of time in a test run. Nozzle diameter : 4 mm, discharge : 3.6 m^3/h, water temperature at heater : 65°C.

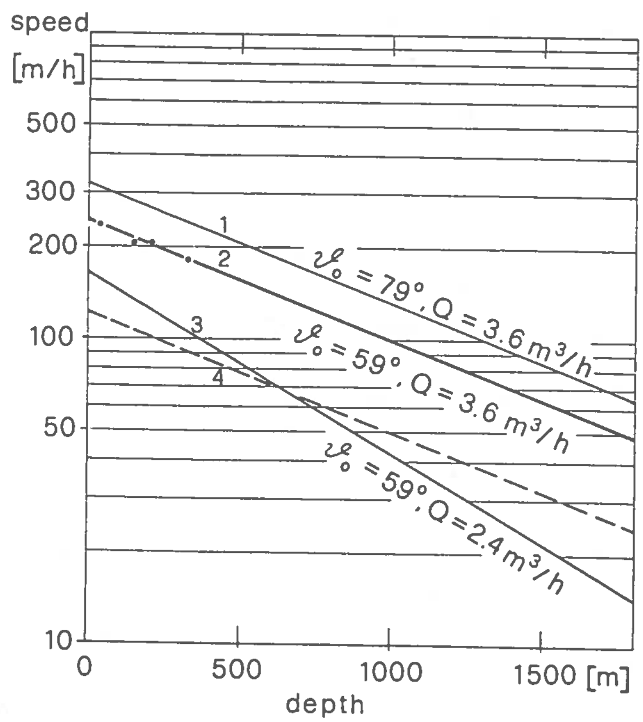


Fig. 5 - Drill speed as a function of depth assuming that R and C* are constant. Data points correspond to the slope of the curve in Fig. 4.

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

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

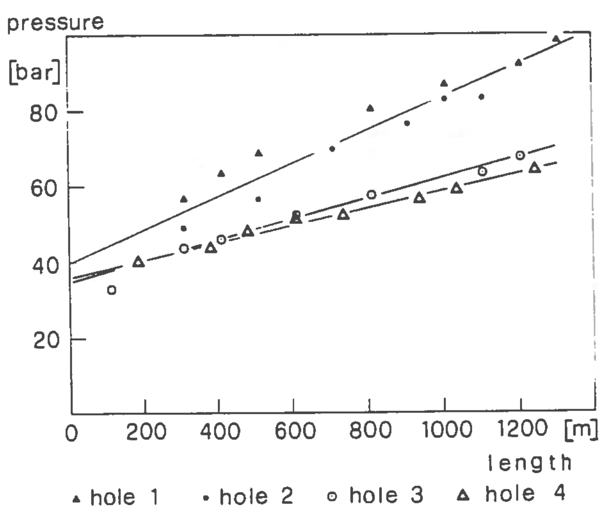


Fig. 6 - Applied pressure versus length of hose recorded during drilling with a discharge of 3.6 m^3/h. At length 0 the pressure corresponds essentially to the loss of pressure head in the nozzle. Additional information is given in the text.

ICE TEMPERATURE

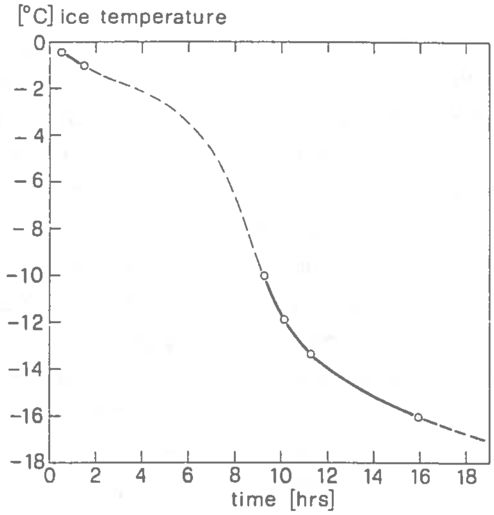
Calibrated thermistors were inserted into boreholes and the temperature recovery was recorded. For example, the plot of temperature versus time in Fig. 7a indicates that the water near the thermistor froze during the first hour and that the hole froze shut within 10 hours or less. The maximum cooling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

FREEZING RATES OF BORE HOLES

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

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

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



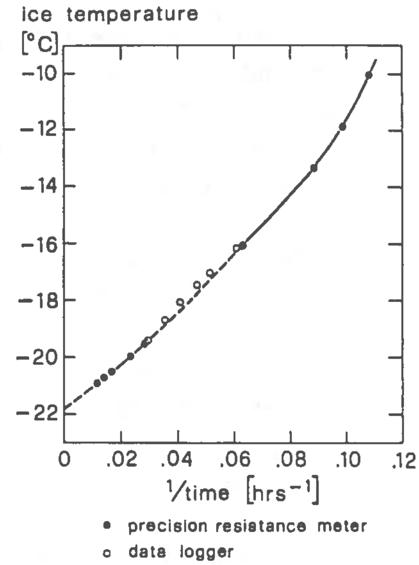


Fig. 7a - Temperature variation shortly after drilling. The thermistor is at 988 m depth. The thin, broken line sketches a typical temperature variation ; no measurements were taken during this time interval.

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

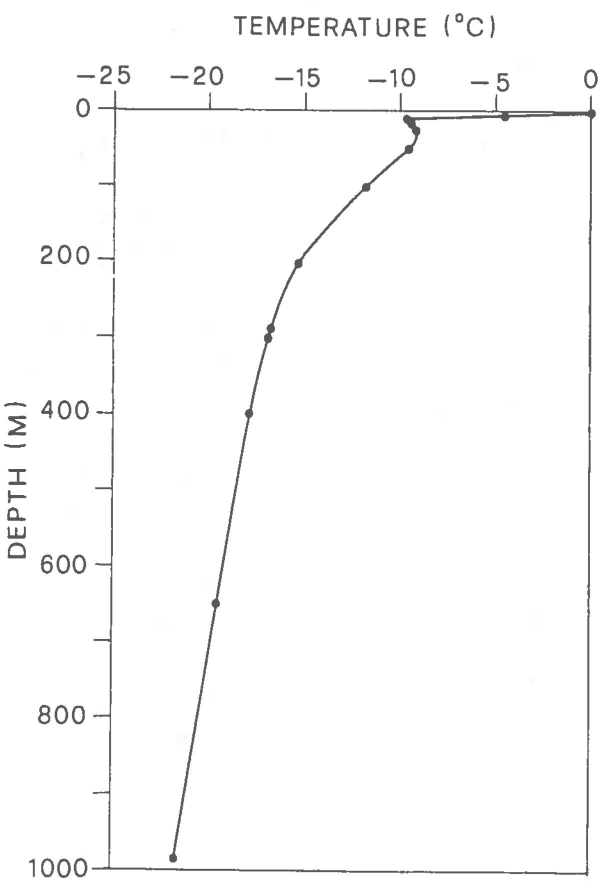
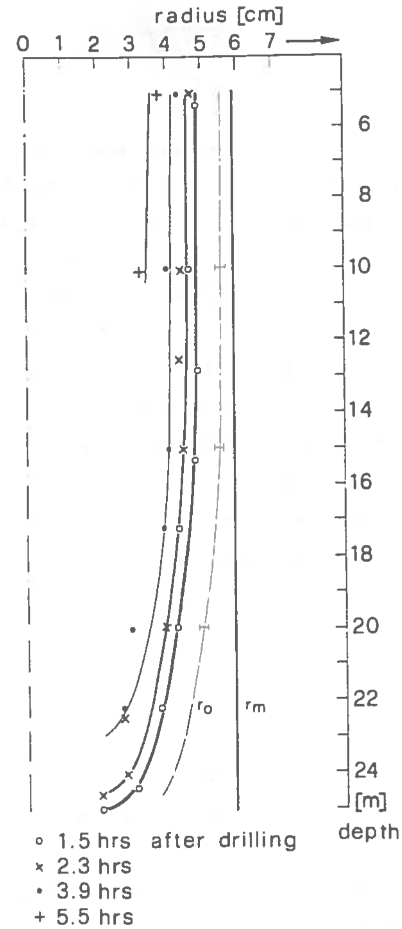


Fig. 8 - Ice temperature profile at the drill site.



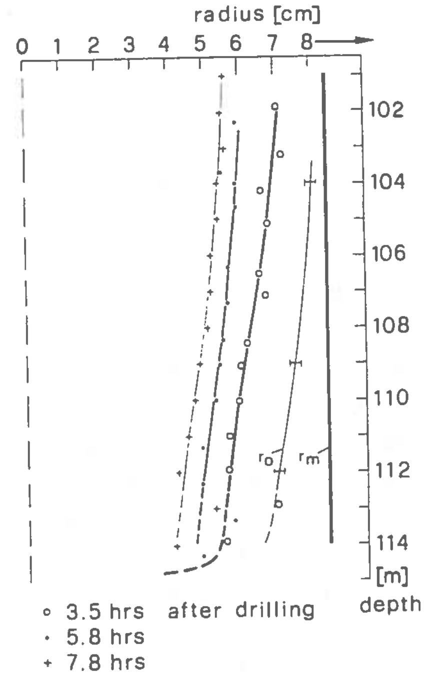


Fig. 9 - Gradual freezing of a borehole drilled to 25 m depth. Ice temperature -9.5°C.

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

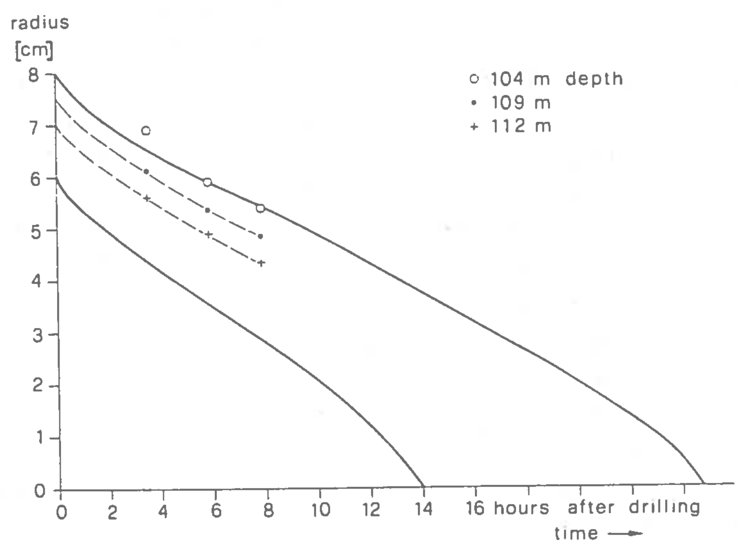


Fig. 11 - Calculated and measured freezing of boreholes at -12°C (data from Fig. 10). The calculated hole radii (fat lines) refer to initial radii r_0 = 6 and r_0 = 8 cm, respectively.

where

S is the drill speed chosen

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

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

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

(b) Heating continued after drilling

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

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

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

where

λ is the thermal conductivity of ice

r_0 is the initial borehole radius.

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

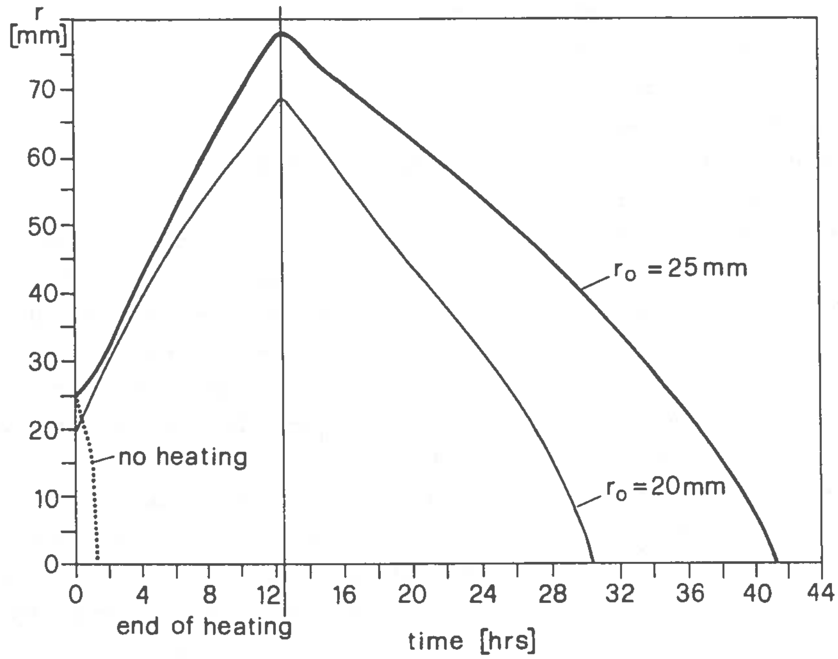


Fig. 12 - Calculated enlargement of a borehole after drilling by heat transfer from the drilling hose and subsequent freezing. Ice temperature : -20°C, assumed heat loss from hose : 150 kcal/(mh) = 174 W/m.

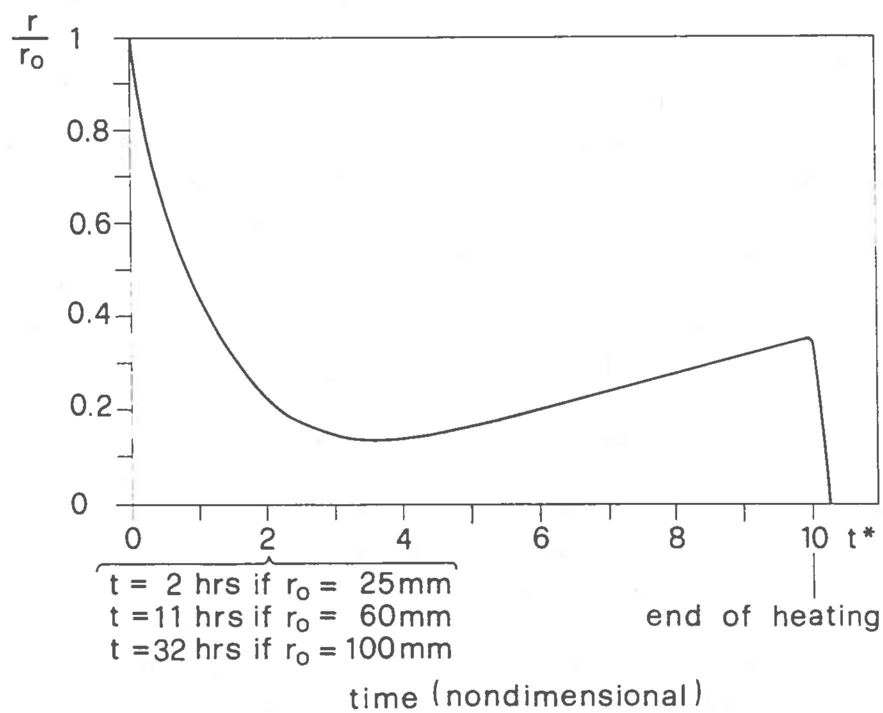


Fig. 13 - Calculated variation of hole radius due to slightly warm hose in hole. Ice temperature : -25°C, assumed heat loss from hose : 73 kcal/(mh) = 85 Watt/m.

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

CONCLUSIONS

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

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

ACKNOWLEDGEMENTS

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

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

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

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A DEEP HOT WATER DRILL SYSTEM WITH POTENTIAL FOR BOTTOM SAMPLING

by

B. Koci
Polar Ice Coring Office
University of Nebraska-Lincoln
940 North 17th Street
Lincoln, Nebraska 68588-0640, U.S.A.

ABSTRACT

During the 1987-88 Antarctic season, we tested a hot water drilling system capable of drilling up to 3,000 meters. By insulating a one inch diameter hose, the heat loss is reduced so water temperature at the nozzle falls off by 2°C/100 m, of water depth. In addition wires incorporated in the jacket allow measurement while drilling to assure hole straightness and large enough diameter to permit instrument raising and lowering. Heat input for this system is 0.5 W.

Some ideas will be presented on drilling sub-glacial material. Saturated till sampling requires a tool used by the well drilling industry for sampling material below the water table while rock sampling and coring frozen till utilize mining technology. The use of additives to enhance drilling rates will also be discussed.

INTRODUCTION

Experience with hot water drilling in cold ice began in 1979 at Dome C in Antarctica. Many holes to depths of 60 m were completed successfully with no problems of freezing encountered despite ambient temperatures approaching -40°C and ice temperatures of -54°C. PICO continued using a small system to drill hundreds of holes successfully.

The need for deeper drilling and recovery of bottom samples requires a high heat input and insulated hose to permit drilling beyond 1000 m. Both are necessary to prevent freeze-up within the hole and to preserve heat within the hose for drilling. An instrumented cable allows drillers to monitor progress of drilling assuring a successful hole each attempt.

This system is an expansion of drill systems currently in use allowing commonality of parts. Six to eight carwash heaters are placed in parallel producing a heat input of 0.5 MW to 0.65 MW depending on flow rates and inlet temperature.

A modified Rodriquez well is used to supply water to a triplex pump which boosts pressure to over 100 bars at 84 l/min. The water is then heated and returned to the drill. Pressures and temperatures at all above hole locations are monitored with standard gauges.

The drill hose is standard synflex 3000, 2.4 cm I.D. which has been modified by wrapping with electrical conductors, a kevlar strength member and an outer neoprene jacket.

The outer diameter is nearly 5 cm requiring a minimum bending radius of 50 cm. This assembly can be produced in single lengths of up to 700 m which can be attached to achieve the desired length. Since the hose is buoyant (200 kg/600 m) weights must be added to the drill stem.

An electronics package (Hancock, 1988) is attached to the upper portion of the drill allowing monitoring of drill progress. Among other things hole diameter, inclination and water outlet temperatures are available to the driller. This is important when planning drilling progress to prevent freezing of the system.

A standard spraying system fulljet 15° nozzle is used to continuously mix water in front of the drill and provide maximum heat transfer coefficient with the ice surface. This type of mixing works well with the slow drilling speed we use to provide access holes.

RESULTS

During the 87-88 austral summer, this system was used successfully to drill two holes at Crary Ice Rise on the Ross Ice Shelf. (Bindschadler, 1988) The deepest of these holes was 480+ m with an additional penetration of 15 m of bottom sediment.

Since heat loss of the hose was limited to 2°C/100 m of hose immersed, extrapolation suggests holes up to 3000 m of depth can be drilled. In addition the large cross sectional area of the hose keeps pressure loss within the hose to 1/4 bar/100 m at a flow rate of 80 l/min.

Placement of thermistors in the hose was done using a Cortland Cable hi-wire cable strengthened with kevlar. This cable is compliant and can survive 30 % stretch suggesting its use in active ice. Thermistors and junctions all survived the freezing process and were giving reasonable data at season end.

SYSTEM SIZE AND FUEL CONSUMPTION

This system is large and bulky despite being able to be separated in smaller pieces the single largest piece is the hose reel and hose which weights 1700 kg and occupies an entire U.S. Air Force pallet. In addition, a 16 kW pump and 10 kW generator are required. Both weigh 200 kg.

Heaters each weigh 125 kg and burn 10 l/hr of diesel or Jet A-1 fuel. This translates to a consumption of 2 l/m diesel plus 8 l/hr of gasoline.

CONCLUSION

This system was designed for use in deep ice or to provide access holes through ice for scientific experiments. In the future bottom sampling can be carried out using either a sampler designed for collecting material in saturated till or for coring rock through use of a packer, screwjack, hydraulic motor and rock coring barrel. We plan to begin testing this system in shallow areas for shallow cores soon and will borrow much of the technology from the mining industry. This should provide access to the other 98 % of the Antarctic geology.

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A DANISH CONTRIBUTION TO THE FAMILY OF HOT-WATER GLACIER DRILLS

by

Ole B. Olesen
The Geological Survey of Greenland

ABSTRACT

A high-pressure hot-water drill has been used successfully down to 400 m in ice with a temperature of -2°C at the margin of the Greenland ice sheet. An average speed of about 5 m per minute for the top 100 m has been achieved. The complete drilling system, inclusive of tools and 600 m of drilling hose, has been reduced to 473 kg with the heaviest single unit weighing 127 kg. The drill system is equipped with a guiding system consisting of a load cell and a built-in inclinometer.

INTRODUCTION

During 1986 glacier-hydrological investigations for a possible hydro-electric power station near Jakobshavn, West Greenland had reached a stage where improved knowledge of subglacial topography and drainage were a decisive factor (Thomsen et al., 1986). As one way to attack this array of problems it was decided to build a hot-water drill which seemed to be the fastest and most reliable system for reaching the bottom of the ice.

The surface topography of the ice sheet is too rough to use sledges so all but the shortest (10-50 m) movement of equipment must be done by helicopter, setting rather strict limits on the weight and bulk of the largest/heaviest items to be moved. As the most common small helicopter operating in Greenland is the Bell 206 Jetranger the maximum weight carried in one haul has to be limited to less than 250 kg. A further restriction is that transport between airport and the ice at the start and end of the season is by a S61N helicopter which is not equipped with a hoist, meaning that all equipment has to be loaded and unloaded by hand. Weight criteria for the design of the heaviest single unit was therefore set at 125 kg making it possible to lift it 1.5 m from the ice up to the cargo door of the helicopter.

EQUIPMENT

The basic requirements for hot-water drilling, moderate amounts of high-temperature water at high pressure, are the same as for industrial high-pressure cleaners. In principle it is possible to buy a commercially available high-pressure cleaner, connect it to the drilling hoses and start drilling right away.

However, commercial systems tend to be very heavy and compact making them almost impossible to handle and very hard to service under field conditions. It was, therefore, decided to use individual components from the commercial systems and modify them to meet our specific needs.

One of the design criteria was that no single unit should weigh more than 125 kg which led to the construction of separate power and heating units. During operations they are bolted together acting as a single unit (see fig. 1) which can be moved by helicopter in a single haul.

Power and pump unit

This unit consists of a 6 kW four-stroke gasoline engine with a 1:2 reduction gear connected to a high-pressure piston pump through a flexible coupling (see fig. 2). At 1750 r.p.m. the pump delivers 18 l/min. of water with a pressure of up to 100 bar at which pressure the relief valve is set. The engine is also connected through a belt drive to a small 0.6 kW 220 v generator which is used for the ignition system in the heater. Fuel consumption is 2.5 l of gasoline per hour. The whole unit is mounted on a stainless steel frame and the total weight is 79 kg.

Heating unit

The heating unit is a water coil with an oil burner (modified for using jet-A1 fuel). Airblower and oil pump are driven by a flexible axle which is connected to the rear end of the generator axle (see fig. 2). Current for the ignition is drawn from the generator.

The water coil is used in a vertical position making it easy to empty when drilling is completed. The air for the burner is blown in from the bottom of the heater, passing between an inner and outer mantle up to the burner which is at the top. This construction ensures preheating of the air and a low outer surface temperature together with a very high heating efficiency. With fuel consumption of 11.6 l/h corresponding to 113 kW and an outlet temperature of 82°C the heating efficiency under field conditions is better than 90 %.

The heating unit is safeguarded by a safety valve, water-flow contact, thermostat, and high-temperature cutoff and is equipped with gauges for temperature and pressure. It is mounted on a stainless steel frame and the weight is 127 kg, slightly more than the design goal of 125 kg.

Drilling hose

This is a 1/2" heat resistant high pressure hose with working limits at 121°C and 138 bar in lengths of 100 m fitted with hydraulic system couplings and weighs 21 kg/100 m. The drill stem is 2 m long with a 25 mm outer diameter and an inner tube of 10 mm with the space between filled with lead in the bottom half. Both tubes are made from stainless steel. The end of the drill stem is fitted with a tapering bronze tip of 180 mm as suggested by Iken et al (1977) and Taylor (1984) with interchangeable stainless steel nozzles of 25 mm. Further equipment is a lightweight tripod with winch and pully (see fig. 3) plus a low-pressure centrifugal pump used when drilling water has to be drawn from farther away.

The total weight of the complete drilling system (with 600 m of high pressure hose) inclusive of tools and spare parts is 473 kg. Table 1 gives a more detailed listing of weights for different parts of the whole system.

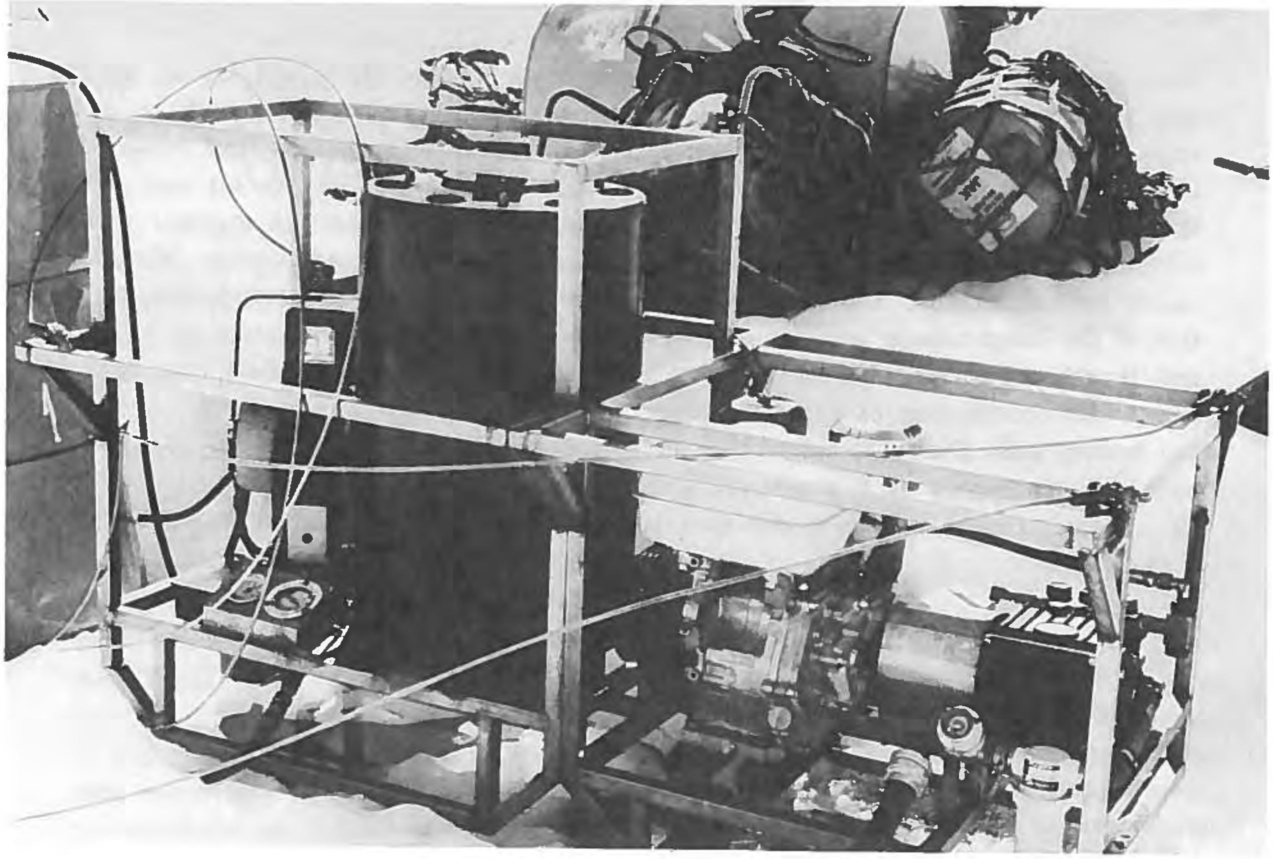

Fig. 1 - Central part of the drilling system. To the right, a gasoline engine and high pressure pump form the power unit. The heating unit is to the left. Units are bolted together for field operation.

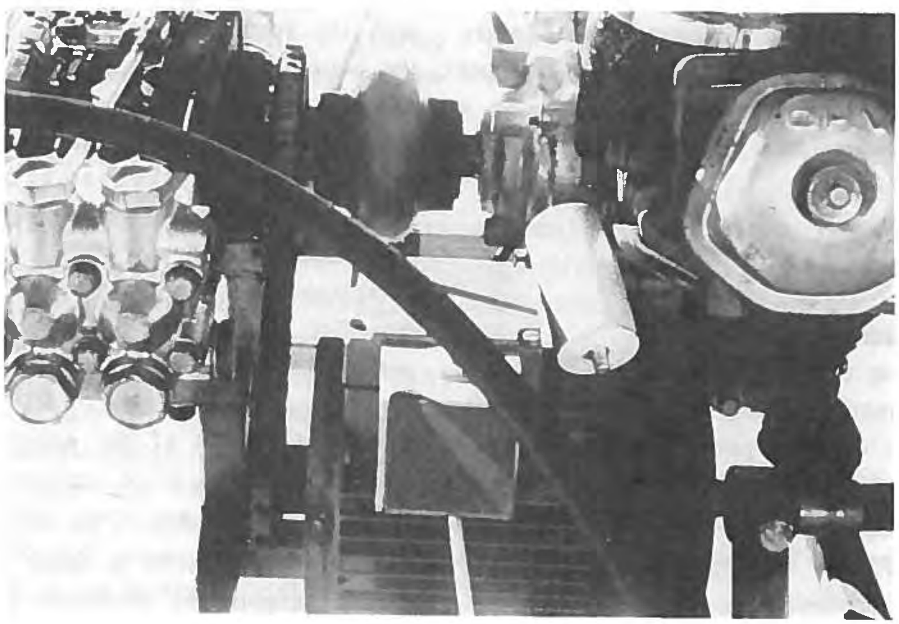

Fig. 2 - Details of power unit hook-up. The hose running diagonally in the figure is the high-pressure water from pump to heater. Note flexible axle from rear end of generator. Safety shield has been removed for clarity.

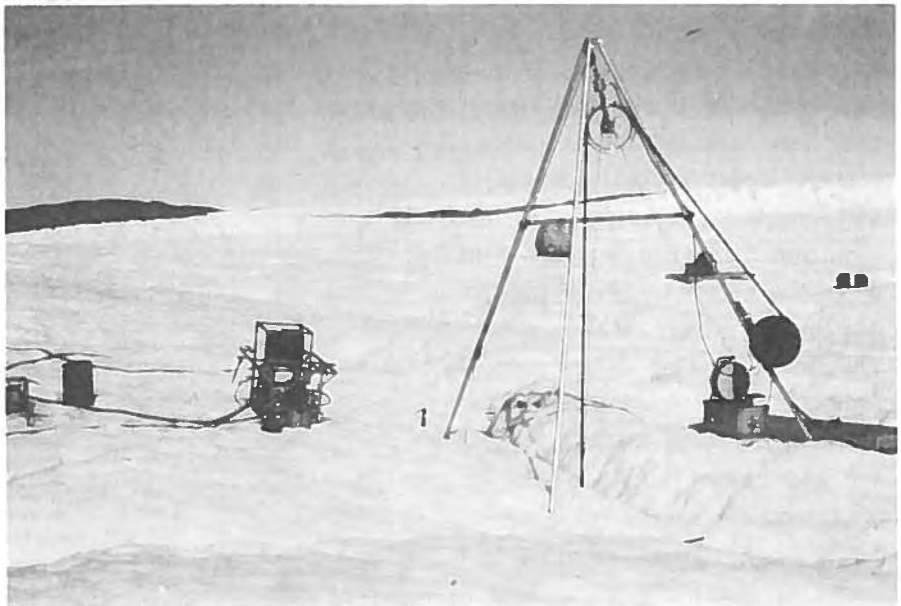

Fig. 3 - Light weight tripod with winch and pulley. The reel for the inclinometer cable is located below the winch.

Table 1 - Breakdown of weights

Power and pump unit	79	kg
Heating unit	127	"
Tripod, winch and pulley	73	"
Drilling hose (600 m)	126	"
Water pump	19	"
Tools and spare parts	16	"
Cables	20	"
Drill stem	6	"
Load cell & inclinometer	7	"

Total	473	kg

CONTROL EQUIPMENT

Inclinometer

In order to monitor tilting of the drill stem a new inclinometer was constructed. The design goal was to avoid hinges or bearings and to make it small enough to fit inside a 32 mm tube on top of the drill stem together with the 10 mm inner tube leading the hot water from the hose to the nozzle. Range should be from 0° to about 10°.

The finally adapted design is based upon the principle of a capacitor. It consists of an acrylic tube with an outer diameter of 28 mm and 1 mm walls closed with lids which fit tightly around the inner 10 mm tube. To make the whole system airtight 0-rings are bolted to the lids with acrylic covers (see fig. 4 and 5). To the inside of the upper lid a copper washer with an outer diameter of 26 mm and an inner diameter of 11 mm and a thickness of 1/10 mm is glued and sealed with a plastic spray. A lead is soldered to the washer and goes through both lid and cover.

The acrylic tube is filled with mercury, through screw holes in the bottom lid, until about 2 mm of space is left. The left-over space is filled with silicone oil no. 200 with a viscosity of 200 cts.

Due to lack of time the necessary electronic system is rather crude and hence too sensitive to temperature changes. Basically it stabilizes an incoming DC voltage, converts it to a 500 kHz AC voltage which is applied to copper washer and mercury as the variable part of a two-capacitor voltage divider. The signal is then rectified, amplified and led to the surface via a three-lead cable running along the hose. The same cable is used to supply the DC voltage from a battery at the drill rig. The outgoing voltage is read off a meter at the winch. The electronic components are wrapped around the inner tube and cast in epoxy which is covered by the metal tube seen in fig. 5

In principle it should be possible to determine directions of tilt (when coupled with a compass) by dividing the washer in segments read off separately. With an area of only 4.36 cm^2 it is, however, possible that the signals will be drowned by noise in the system.

Load cell

To measure the tension of the hose as in the USGS system (Taylor 1984) a load cell is placed between the top of the tripod and the pulley. It is a commercial unit, temperature compensated with a load capacity of 500 kg and an overall accuracy of 0.1 % (factory figures). The load cell is run by the same battery as the inclinometer and is read off a second meter at the winch.

FIELD EXPERIENCE

During the two field seasons 1987 and 1988 a total of 5657 m has been drilled with the deepest hole being 390 m. In 1987 a nozzle with an inner diameter of 2.7 mm was used for all holes and this gave a pump pressure of 35 bar with one length of 100 m hose. The 1988 drillings were done with a 2.5 mm nozzle which required a pump pressure of 50 bar.

As the first drilling already showed that the equipment fulfilled expectations of a drilling speed of 2-3 m/min. only a few holes were actually timed with the results shown in Table 2. During drilling the hoses are stretched out on the ice and are successively connected as drilling progresses and the measurements refer to the time used until the next 100 m length of hose has to be connected. No corrections have been attempted to compensate for "difficult" drilling conditions as when the drill penetrates layers of ice with debris. On the

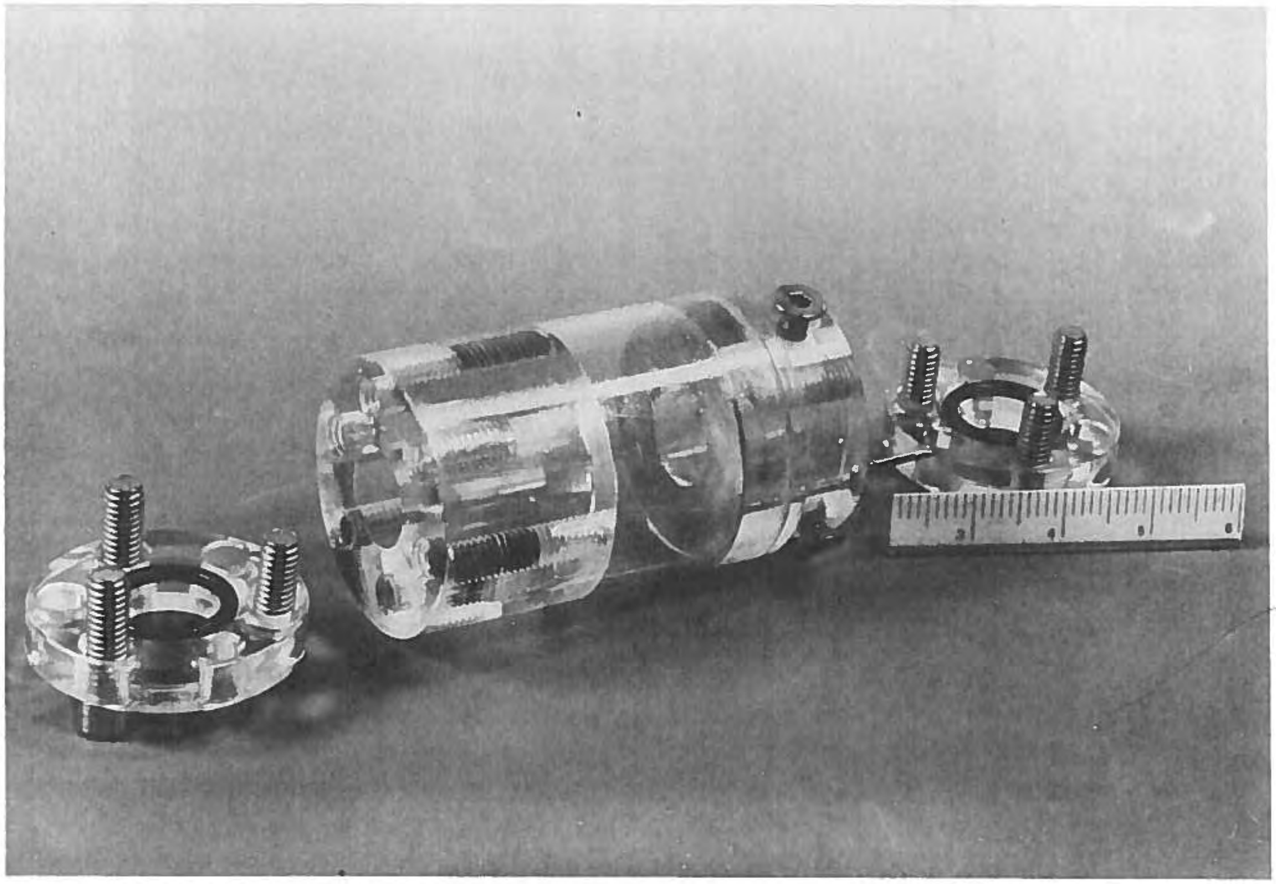

Fig. 4 - Acrylic part of the inclinometer with the top part facing right. For details see text.

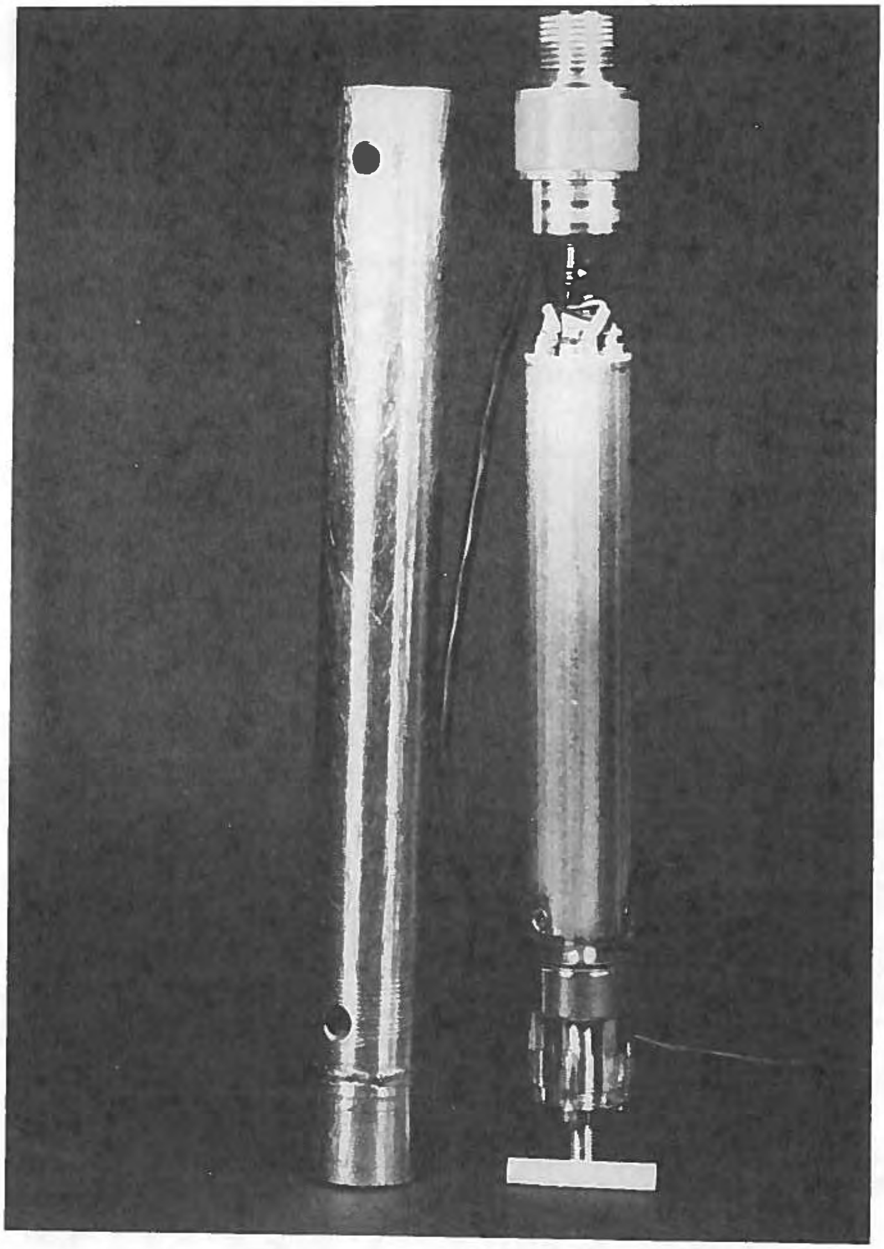

Fig. 5 - Inclinometer with protective cover taken off. The bottom part is the "variable capacitor" with the electronic system covered by the metal tube. Total length of system is 31 cm. Scale at the bottom is 4 cm.

Table 2 - Drilling speed and depth for hot-water jet Påkitsup akuliarusersua, Jakobshavn, West Greenland August 1987. Units are metre/minute.

	Depth Intervals				Max Depth
	0 - 90 m	90 - 190 m	190 - 290 m	> 290 m	m
	4.1	2.6	2.2	-	298
	6.0	-	-	-	305
	5.6	-	-	-	270
	6.4	3.6	2.1	1.1	382
	4.5	4.0	-	–	298
Mean drilling speed	5.2	3.3	2.1	1.1	

other hand it should be noted that none of the holes listed in Table 2 encountered the more extreme conditions when drilling through a 5-10 m layer, very often between 150 and 250 m depth, required 1-2 hours.
The load cell and inclinometer (which were both added in the 1988 field season) worked very well together, immediately alerting the operator to any slowing of progress or deviation from the vertical. They were most useful when debris layers were encountered as the operator could add pressure on the drill tip by paying out more hose, as long as the drill stem remained vertical. This procedure often resulted in a more rapid penetration than when the drill tip had little or no contact with the ice. When a constant pressure had been maintained for at least half an hour and no progress resulted it was assumed that the bottom had been reached.

COMMENTS

Both power and heating unit have worked most satisfactorily as during the two field seasons drillings were never stopped due to any malfunctioning in either unit. However, they were both destroyed under a helicopter operation at the end of the 1988 season and they will be rebuilt after the same concept.
As for the load cell the present millivolt signal should be converted to a weight read-out as this would be very helpful, e.g. when packing helicopter loads.
The electronics of the inclinometer must be changed as it is presently much too sensitive to temperature changes. During operation in 1988 it had to be reset every time a new hose was added. This was done by halting drilling until the temperature at the inclinometer had reached a new equilibrium and using the subsequent reading as a zero point. Together with a temperature compensation the output from the inclinometer should be changed from the present voltage to a frequency signal. Also the silicone oil used in the present system should be exchanged with one of lower viscosity as the hydraulic damping effect is a little too high.

Major commercially available units used in the drilling system.*

Burner and heater
K.E.W. Industri. Heater type 03V rated at 103 kW, with thermostat, high-temperature cutoff, safety valva, water-flow contact, temperature and pressure gauges.

Pump
Interpump. Model W912 with ceramic pistons, rated at 18 l per min. at 1750 r.p.m. and maximum pressure 100 bar with safety valve set at the same pressure.

Engine
Honda. Type GX 240 gasoline engine with 1:2 reduction gear rated at 6 kW (8 HP) at 3600 r.p.m. Engine and pump are connected via a flexible coupling on the gear shaft.

Generator
Grundfos International. Type MG 7132-14 rated at 220v, 2.6A, 50 Hz at 2810 r.p.m. Generator is connected to the engine with a belt drive counterbalancing the difference between the gear shafts 1750 r.p.m. and the 2810 required.

Centrifugal pump
Honda. Type WB 10 rated at 150 l/min. with max. 38 m of water level difference.

High pressure hoses
Imperial Eastman thermoplastic hose type HK 408 SAE 107 R A 3465, 12.7 mm (1/2") inner diameter, rated working pressure 138 bar, temperature range -46°C - 121°C constant. Weight in air is 21 kg/100m.

* Use of brand names is for identification purposes only and does not constitute endorsement by the Geological Survey of Greenland.

ACKNOWLEDGEMENTS

In the initial stages of design H. Röthlisberger and A. Iken of ETH, Zürich, were most helpful in discussions of the concept. Electronics for the inclinometer were designed by E. Hansen, GGU. A. Clausen played an integral part in the construction and built the mechanical system.

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ICE CORE PROCESSING

NEW METHODS IN ICE CORE PROCESSING

by

B. Stauffer, J. Burkhalter and A. Sigg
Physikalisches Institut
Universität Bern
Bern, Switzerland

ABSTRACT

Core processing includes the inspection, registration, labelling and packing of ice cores as well as first measurements in the field. The methods of core processing applied during core drillings at Dye 3 and South Pole are presented. A modified version that will be applied in summer 1989 in Central Greenland is discussed in more detail. It includes the cutting and melting of subcores and the measurement of certain impurity concentrations (e.g. H_2O_2) continuously along the core in the field.

INTRODUCTION

It is evident that ice core processing belongs to any ice core drilling. It has to include at least the inspection, registration and labelling of the ice cores. An extended ice core processing in the field is especially needed if different laboratories are involved in the analyses of the ice cores later in the laboratory. The goals of an extended core processing are especially :

- to give a detailed documentation of the ice core which allows later to any core user to select the samples best suited for his analyses.

- to perform a preliminary dating already in the field which allows to preselect samples.

- to make analyses already in the field for components which might change during transportation and storage or which can be measured much more efficiently in the field.

A core processing that accomplishes at least partly these criteria, was applied during the deep core drilling at Dye 3 (1979-1981) and during the core drilling at South Pole by PICO 1983 and 1984. An extended core processing is also planned for the Eurocore drilling in Central Greenland in 1989. The operation of the core processing applied at Dye 3 and South Pole will shortly be presented before discussing the modified version of a core processing planned for Eurocore.

LAYOUT AND OPERATION

At Dye 3 the ice cores were inspected, measured, marked and recorded in a one to one scale on millimeter paper. The meter marks made on the ice core itself ensured that all investigators were using the same depth scale within a few millimeters. The core was then fixed in a frame and in a second step the core was splitted parallel to the core axis with a specially constructed band saw. The upper core segment (core diameter : 100 mm, height of segment : 32 mm) was used mainly for isotope analyses and dust concentration measurements. The samples for isotope analyses were cut to size and packed individually in the field. The dust measurements were also done to a large part already in the field (Hammer et al., 1985). The cutting surface of the remaining part was then planished by a microtome blade. In a third step the electrical conductivity was measured on the smooth and clean surface along the core (Hammer, 1980). The electrical conductivity results allowed to detect tracers of volcanic eruptions already in the field and together with the dust measurements, they allowed also to detect clearly the transition from the last glaciation to the Holocene. After the electrical conductivity measurements, the ice core was taken off the frame, cut in meter pieces, packed and labelled.

At South Pole station, ice cores from South Pole and from Siple Station were processed. The ice cores were first inpected, measured and marked. To obtain a flat and clean surface a very thin segment of the core was cut away with the bandsaw and discarded. The cutting surface was planished by a microtome blade. The smooth and clean surface was recorded in a third step continuously on video tape. Subsequently the electrical conductivity was measured on the same surface. The core was then splitted in two parts with an ordinary band saw and packed and labelled. The video recording was very useful as documentation of the ice cores. It is as informative as the recording by hand on millimeter paper, it is very easy to handle and can be copied and distributed to different core users. Core processing at Dye 3 and South Pole needed about 4 to 5 people to process 20 m ice core per day.

During Eurocore, an ice core drilling operation that will be performed in summer 1989 in Central Greenland, a core processing according to the layout shown in fig. 1 will be used. More analyses shall be performed already in the field. By the availability of new analytical techniques, which allow to measure very fast low impurity concentrations in small samples, it is well justified to measure several parameters already in the field. However, it has to be kept in mind, that each step for a one meter ice core has to be performed in less than about 30 minutes, in order not to slow down the whole core processing. Most of the new analytical methods are based on a modified flow injection technique, using a continuous flow of the melted sample. The question arises, whether one subcore should be extracted and melted in order to distribute the water to the different analytical instruments, or whether each analysis should be provided with a separate subcore and a separate melting device. We decided to use different subcores. The reasons as well as the method of cutting and melting the subcore will be discussed in the next chapter.

DIFFERENT COMPONENTS OF THE CORE PROCESSING LINE

Band saw :
We made a relatively great effort to construct a band saw which allows to split an ice core with a very flat and precise cut parallel to the core axis. The core is fixed in its frame to a stable bed-plate of a length of 3500 mm and a weight of 160 kg. The bandsaw is driven by a 0.5 kW electrical D.C. motor. Both wheels are counter-balanced. The saw blades are of the cross tooth system and have a thickness of 0.65 mm. The speed of the saw blade is variable. Best results were obtained with a velocity of about 4 m/s. The band saw moves automatically on a rail system along the bed-plate. The speed of advancement is also variable. For tests we used velocities between 8 and 20 mm/s. The band saw allows to cut a thin plate of only 8 mm thickness all along a one meter ice core.

Milling tool :

The cutting surface made with the band saw is flat but not clean and smooth enough to perform e.g. electrical conductivity measurements. Until present we used a microtome blade to planish the surface, but now we have constructed a milling device which gives a surface as clean and even smoother than with the microtome blade in less time. The milling cutter has a diameter of 160 mm. It contains 9 hard-metal cutters and rotates with 3 000 rpm. A layer of 1 mm at maximum can be milled away in one step. With an advancement of 8 mm/s or less, a smooth and clean surface is obtained.

Video recording

For the video recording we move the video camera (Sony V-8e) over the ice core which is illuminated from below. The polished cutting surface is recorder. The advancement velocity is 8 mm/s.

Preparation and melting of "subcores" :

It would be most efficient to separate one part of the ice core by a band- or circular saw, to melt this part continuously with a constant melting rate and to distribute the meltwater to the different analytical devices. The new analytical methods are fast and easy to operate, but occasionally there can occur interruptions in the analyses due to a failure in any of the analytical systems. Any interruption on one device would hold up all other measurements and therefore the whole core processing, or measurements for one component would be lost for a certain core length. We decided therefore to cut several subcores with a band saw and to use for each subcore an individual melting device. The principle of a simple melting device is shown in fig. 2. It is suitable for components which are not very susceptible to contamination. It has been applied successfully for continuous measurements of hydrogen peroxyde during a field operation at Dye 3 in summer 1988. A subcore with a rectangular cross section of about 8 x 10 mm^2 is cut with a band saw. The subcore is then continuously melted at a rate of 1 mm/s. The meltwater is pumped to a heated box where the concentration is measured continuously. The power needed to heat and melt the ice is 30 Watt, heat loss not included. The heating element consists of a teflon coated aluminium cylinder which can be heated up to 120 Watt. The heating power is electronically regulated in order to reach a rather constant melting rate. The melting rate is recorded by measuring the length of the remaining part of the subcore with a potentiometer circuit. Fig. 3 shows examples of H_2O_2 concentration profiles along two core sections of 1 meter each from the Dye 3 ice core. The analyses was performed immediately after core recovery. The results from two neighbouring subcores of the same depth interval show the excellent reproducibility of the method for H_2O_2.

However, for parameters like Ca++ and HCHO which are more susceptible to contamination, only the meltwater of the inner part of the subcore can be used. We are constructing therefore a special melting device for these components which allows to separate the meltwater from the surface of the subcore. The minimum subcore cross section required for this method is 15 x 20 mm^2.

There is an alternative to the melting of subcores. Hammer (1985) has used a kind of soldering iron to melt a small groove into the ice core itself. The meltwater is pumped away continuously. The method offers more flexibility, especially in case of fractured cores, since the melting track has not to follow necessarily a straight line. However, the method is laborious, especially if several continuous samples have to be extracted, and further we are afraid that this procedure could produce thermal cracks on the remaining core.

SOME REMARKS ON ANALYTICAL METHODS

As an example of a continuous flow analysis (CFA) the measurement of the H_2O_2 concentration shall be discussed. The meltwater is pumped off the melting device with a pumping rate exceeding the melting rate in order to separate small parcels of meltwater with air bubbles. The water is pumped through a heated tube into a thermostated box where all analytical instruments are placed. There, in a first step, the air segments are removed from the sample stream. The flow rate to the debubbler is about 6.4 ml/min, after the debubbler about 0.83 ml/min. Immediately after the debubbler a reagens solution is added with a rate of 0.45 ml/min to the meltwater. The reagens solution contains 0.03 M (mol/l) borate buffer (pH = 7.8), 2 10^{-3} M 4-ethylphenol and 3.6 mg/l peroxidase. Hydrogen peroxyde forms dimers of 4-ethylphenol, catalysed by the enzyme peroxidase. This dimer can be detected fluorometrically (absorption maximum : 310 nm, emission maximum : 400 nm). We have constructed a filter fluorimeter, using a cadmium lamp with a strong emission line at 326 nm as light source and with a photomultiplier as detector of the fluorescence light.

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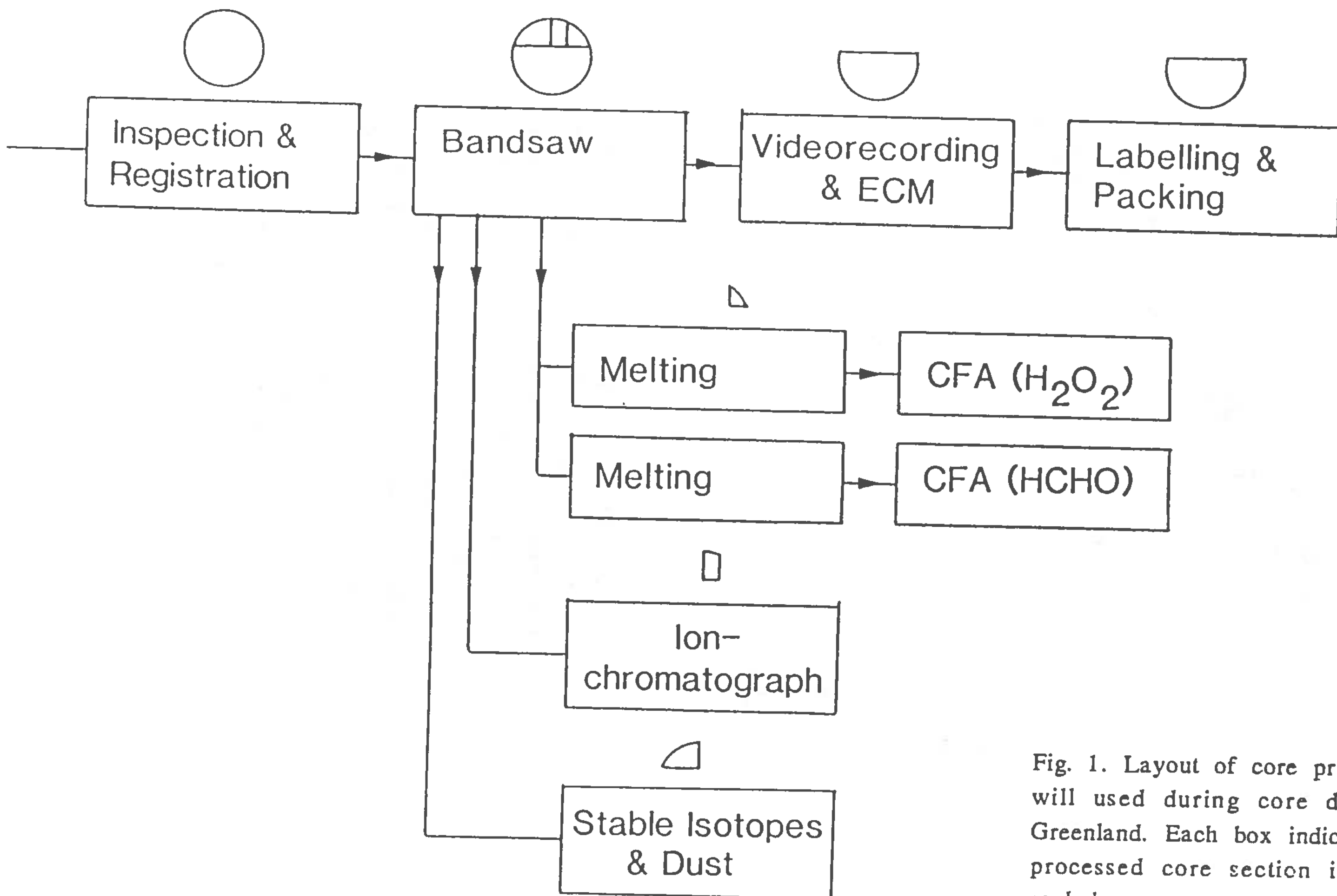


Fig. 1. Layout of core processing line which will used during core drilling in Central Greenland. Each box indicates one step. The processed core section is indicated above each box.

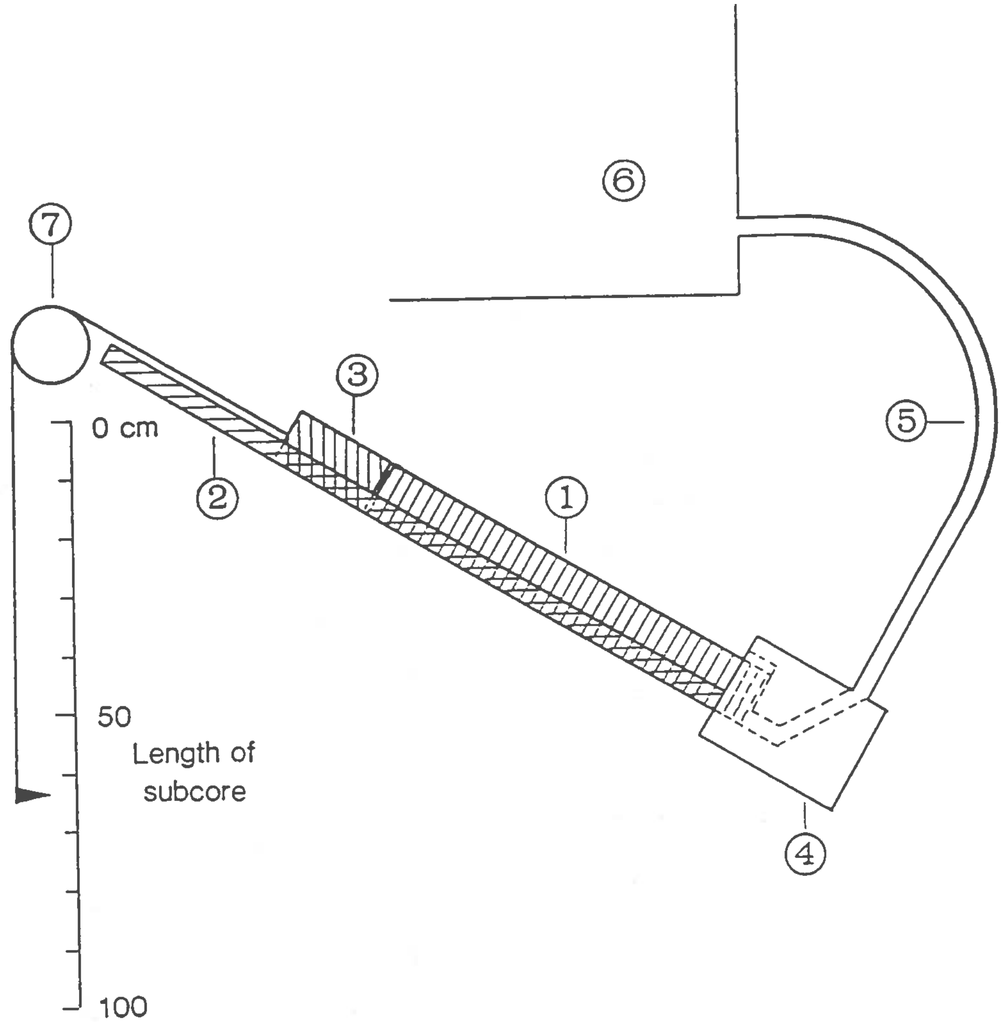
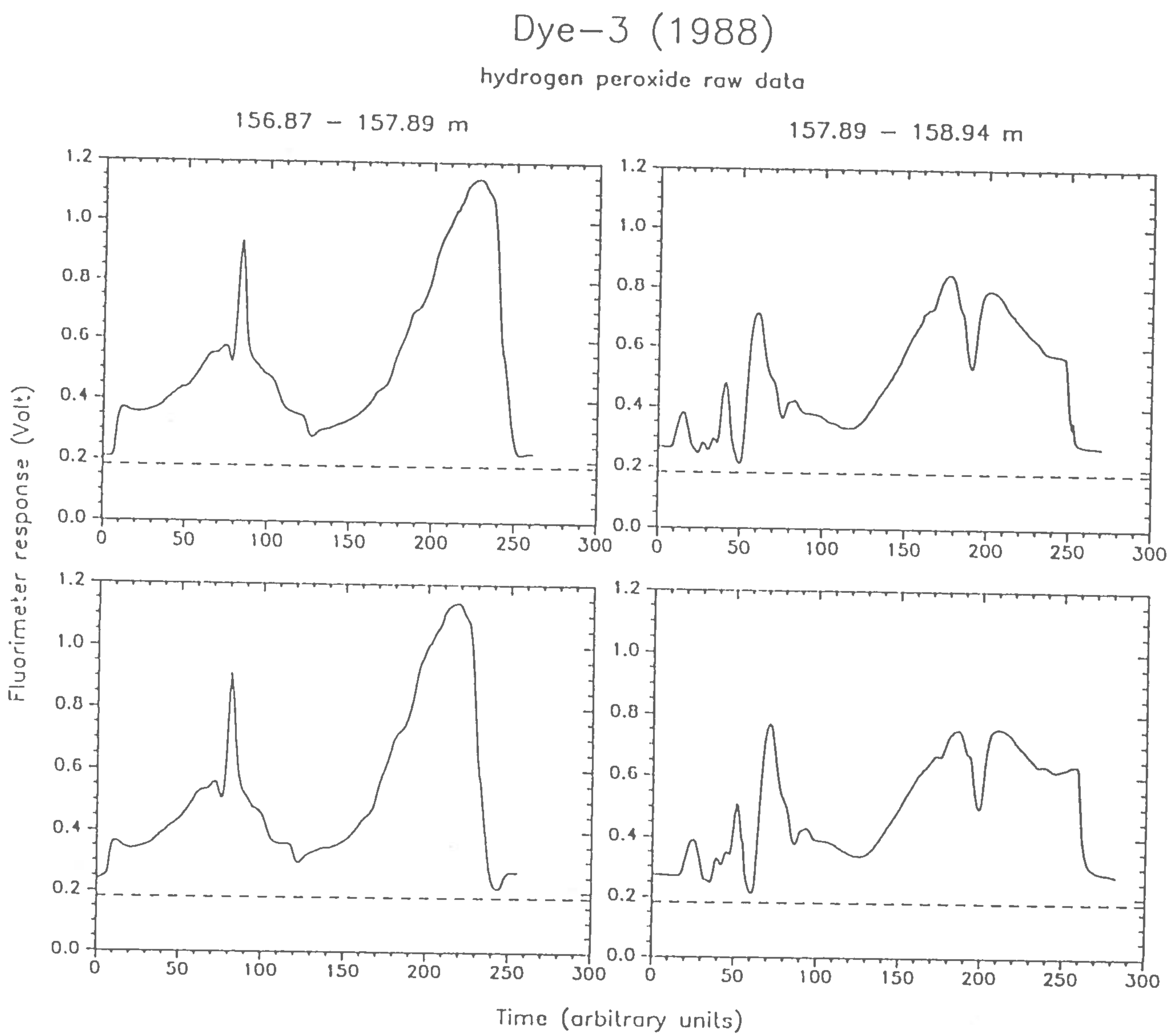


Fig. 2. Schematic of simple subcore melting device. The subcore (1) with a rectangular cross section of 8 x 10 mm^2 glides in a teflon coated channel (2). It is pressed with a weight (3) against a teflon coated aluminium cylinder (4) with an electronically regulated heater. The meltwater is pumped through a heated hose (5) to a thermostated box (6) where the concentration is measured. The melting rate is about 1 mm/s. The length of the remaining part of the subcore is measured with a potentiometer circuit (7).



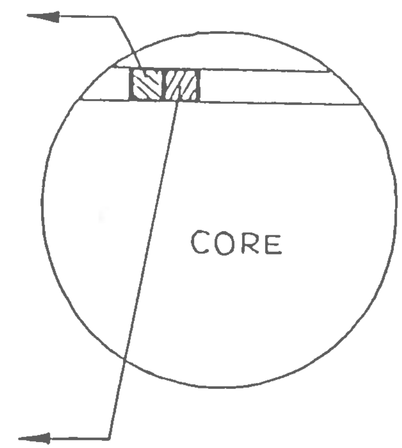


Fig. 3. Examples of H_2O_2 concentration measurements on two different ice cores of 1 m length each. The measurements were performed on two neighbouring subcores in order to test the reproducibility of the analysis.

THERMAL DRILLING

INVESTIGATION OF ICE AND ROCK DRILLING BY MELTING

by

V.S. Litvinenko
Candidate of Technical Sciences
Prorector, Leningrad Mining Institute
Leningrad, U.S.S.R.

ABSTRACT

Considerable experience of the Leningrad Mining Institute in deep borehole drilling by melting in Antarctica and in Arctic Ocean islands as well as successfull experiments in rock drilling by melting confirm the possibility that this new method of borehole drilling provides certain important advantages. Many technological processes are followed by melting of solid bodies in contact with surface heated up to a temperature which is higher than the melting point. The melt which forms flows from the heated surface or melting sample under the action of an impressed force. This method (combined with the others) is used in mining when sinking shafts, for quick ground consolidation of quicksands. The essence of this method is in installing a heater into the thickness of the quick grounds to be traversed. When current passes through the electrodes of the heater, electrons come into collision with atoms of the conducter lattices and so electric energy is transformed into heat energy. The conducter (heater) is heated to a high temperature and melts the surrounding quickground. The idea of openings (holes) sunk by melting provides for 3 most important advantages :

- using of drills with hoist electrical cable, which eliminates the necessity of drill pipes and of labour-consuming and prolonged descent-hoist operations ;

- supporting (when drilling) of hazardous or fissured rocks because through solidification of the hole walls by the melt which is over the penetrator, which eliminates the necessity of a casing, of expensive work on shaft lining or of plugging ;

- more effective and wider application of the methods of logging and well geophysics due to the absence of the action of steel casing screening.

Considerable experience in the field of drilling by melting in Antarctica and in Arctic Ocean island as well as successful experiments in rock drilling by melting /I/ carried out by the Leningrad Mining Institute confirm both the principal probability of this new method of probe drilling and the real possibility of the practical achievement of the above mentioned advantages. This is proved by the common tendency towards energy concentration increase in the face by traditional methods of machine drilling /I/ and by the presence and availability of new alloys and composite materials possessing rather high thermal stability and other necessary properties. Moreover, the results obtained in theoretical works /I,2/ prove that the main but practically the only difficulty of the realization this method is ensuring of penetrator long-term operation at the temperature level of 1200 - 1600° C.

Rock drilling by melting, i.e. borehole formation, is the result of rock melting up to viscous-plastic state due to the contact heat transmission and to melt pressing out over the penetrator with glassy smooth walls. Formation is the result of complex heat exchange and hydrodynamic processes. Complete and exact mathematical description of these processes and their interrelation is too difficult. The difficulties prevented design engineers from being grounded in the procedures of penetrator construction and rock drilling by melting. Ice drilling-melting analitical expressions /I/, based on a number of simplifying assumptions, made it possible to obtain calculated dependences for the determination of all construction and technological parameters with quite satisfactory exactitude. Experience of thermal drills with cable development and their successfull introduction in real field conditions confirmed above mentioned dependence /I,2/. However, their direct application for technical and technological calculations, related with rock drilling by melting can't be successful because of important differences in ice and rock properties, temperature level, materials for tool elements and character of processes.

The aim is to find an approximate analitical solution to the problem of rock drilling by finding the dependence of melting velocity on the main construction and technological parameters. Describing this complex process through calculation and analysis will aid the development of optimal penetrator construction and effective drilling technology.

To take into account the influence of thermophysical properties, natural temperature and rock state, construction dimensions, thermal capacity and the properties of the penetrator material as well as the state, properties and movement regime of melting rock surrouding the penetrator, flow rate, properties and the temperature of washing which cools the penetrator, it is necessary to find the solution of a task set in the case of drilling by melting process. The established process of heat exchange when drilling by melting comes very quickly and it is the most typical for interrelation analysis of the determining factors. This process can be simply described mathematically based on the theory of moving heat sources /I/ according to which the temperature field in rock mass is a constant one (quasi-stationary) in the coordinate system moving with the penetration.

A simple variant of drilling without core sampling (continuous face) is given below.

The penetrator shape is a body in rotation of "chain line" around its vertical axis. For simplicity it must be a one-dimensional problem supposing a uniform heat distribution from the working surface of the penetrator to the surrounding mass. In a given case such simplicity is quite permissible as the drilling-melting process is a dynamic one and in the course of this process a quasi-stationary temperature field in a rock mass surrounding the penetrator is formed. Heat disturbance depth is insignificant because of the small thermal conductivity of rock and because it is constant in a system of moving coordinates related with the penetrator. It is quite comparable both in axial and in radial direction. Furthermore, heat which is dissipated in the surrounding rock mass during drilling by the melting process constitues a small portion of the heat being absorbed for rock melting and subsequent melt overheat. Therefore, a possible inaccuracy in estimation of a given portion of heat can be neglected.

The penetrator with an electric resistance type heaterin its central part and with a system of forced cooling of main elements is considered as a body of uniformly distributed heat source. Any heater of this type has a limited specific volume heating capacity determined by its construction, properties of materials, period of operation. An active thermal capacity of penetrator is N. When drilling by melting process heat is consumed for overheat of surrounding melt Q_1, latent melting heat Q_2 and heating of surrounding rock mass from its natural temperature to the melting point Q_3. Thus :

$$N = Q_1 + Q_2 + Q_3. \qquad (I)$$

As the thickness of melt layer under working surface of penetrator is small, temperature distribution through its thickness can be considered approximately rectilinear and melt overheat temperature is taken as an arithmetic mean between the temperature of penetrator surface and rock melting temperature (transition between solid-liquid states).

Three equations with three unknown quantities were obtained by analysis taking into account accepted assumptions :

- drilling by melting velocity ;
- penetrator surface temperature ;
- average thickness of melt layer.

As a result of joint solution of these equations, an analytical expression for the dependence of drilling velocity on the main technological and constructive parameters in the form of transcendental equation :

$$\frac{N_a - \rho_\Pi [\Phi F_z + (T_{arp} - T_\Pi) C_\Pi F] \upsilon}{C_p \rho_p F_z \upsilon} = \frac{\rho_\Pi \upsilon}{4 \lambda_p} \left[\Phi \frac{F_z}{F} + (T_{arp} - T_\Pi) C_\Pi\right] \times \sqrt[3]{\frac{\lambda \upsilon \rho_p f [(R^2 + 2f^2) \operatorname{sh} R/f - 2 f R \operatorname{ch} R/f]}{2[2p - f g \rho_p (\operatorname{ch} R/f - 1)]}}, \qquad (2)$$

N_a - penetrator active power, W ;
υ - mechanical velocity of drilling by melting, m/sec ;

F - penetrator surface area, m^2 ;
F_z - hole (face) cross-section, m^2 ;
R - radius of penetrator upper end face, m ;

Φ - specific heat of rock melting, J/kg ;

ρ_Π, ρ_p - rock, melt density, kg/m^3 ;

C_Π, C_p - specific mass heat capacity of rock, melt, J/(kg.°C) ;

f - chain line parameter ;

λ_p - melt thermal conductivity index, W/(m.°C) ;

λ - hydraulic resistance index (when melt moves) ;

p - specific axial load, Pf ;

g - acceleration due to gravity, m/sec^2.

The equation obtained for drilling by melting velocity relates all the determining factors of the process : penetrator constructive parameters, its active thermal capacity, axial load on the face as well as thermophysical properties of rock drilled and its melt.

Authenticity of complex and multifactor process of drilling by melting depends mainly on the determination and accuracy of the initial parameters and on the objectivity of experimental results registered. If penetrator construction parameters and drilling process technological parameters (active thermal capacity and axial load) are known beforehand and results of the process (drilling by melting velocity) can be fixed exactly in the experiment, authentic determination of rock thermophysical properties and all the more its melt offer serious difficulties as their properties change greatly. The above mentioned determination is an independent scientific problem. Therefore, rock (namely basalt) physical and thermophysical properties were taken from actual data obtained in the experiment carried out by laboratory in University of California, Los Alamos (U.S.A.) /2/.

Application of high temperature energy generator in the face will permit drilling without the use of drill pipe string, substituting hoist electrical cable : this will provide not only minimum losses through energy transfer from the surface, but also a possibility of full automation of drilling by the melting process.

The practical use of the new prospective method of drilling by rock melting is already possible and advisible when drilling in snow and firn and ice deposits, in loose rocks cemented by ice, on geotherms, in salt deposits, plugging by easily melted materials, for earth fall and pit edge consolidation, for pipe line in urban facilities etc. It can provide a real economic benefit.

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ELECTROCHAUDE : RECENT DEVELOPMENT IN BOREHOLE DRILLING

by

Claude Rado, Claude Girard and Jacky Perrin
Laboratoire de Glaciologie et Géophysique de l'Environnement
Centre National de la Recherche Scientifique
Grenoble, France.

In order to study different aspects of glaciers, the scientists need good quality cores, but also holes bored in the ice. The LGGE has developed core drilling systems and different kinds of boring systems :

- A hot water drill very efficient but bulky and heavy equipment. Its transportation from the valley to glaciers needs the use of a helicopter.

- A steam drill, a light and compact device, portable by men, which is used to drive in wooden stakes. Its efficiency decreases below 15 m deep because of the hydrostatic pressure of the water in the hole.

- A hot point drill, in which an electrical heating element is embeded in silver. It allowed us to measure ice thickness and to put in metallic wires for deformation measurements by inclinometry. But it has three main disadvantages :

- the cost of the head due to both the silver price and the sophisticated fabrication.

- it can be overheated if not immersed in water and can be destroyed.

- it loses its efficiency when the ice contains much rock debris.

For these reasons, we developed a new system called Electrochaude.

DESCRIPTION (Fig. 1)

The external part is a stainless steel tube of 28 mm in diameter and 1.6 m long.

Beginning at the top we find :

- The cable anchorage and the electrical connection.

- The pump (Fig. 2)
  It is an electromagnetic pump, supplied by alternating current with a diode in series which suppresses one wave. The piston is a magnetic core and moves alternately at the frequency of the power supply.

- A filter stops even the finest solid impurities.

- The internal ceramic tube has two functions :

  - as a water duct,

- as a heating element housing.

It has a 12 mm external diameter and 8 mm internal diameter.

- The Nichrome heating wire is coiled helically. It was calculated to dissipate more than 1.6 kW in air without damage.

- The nozzle, made of brass. Its shape was determined according to Taylor (1984).

Initially, the nozzle had a short parabolic shape and the water flow was adjusted by a needle valve. A new shape, having a long, smooth parabolic taper, increased the drilling rate from 8.5 to 14 m/h.

Tips with different size holes can be screwed to the nozzle end.

OPERATION

Water is sucked through the filter, pumped into the ceramic tube were it is warmed by the heating element. It flows as a steady jet, powerful enough to scatter the insulating layer of sand at the hole bottom.

The water jet temperature is about 35°C.

The electrical cable is hand held so that the drill is always suspended.

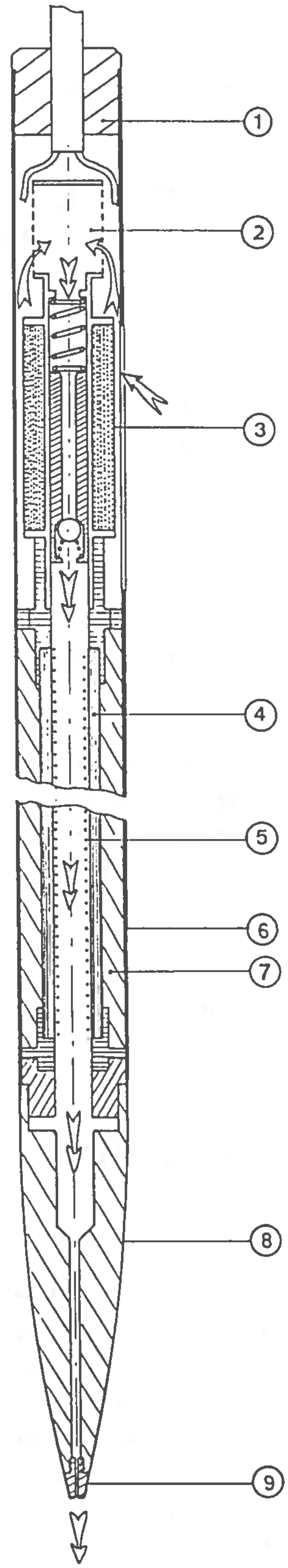

Fig. 1 Schematic diagram of the Electrochaude drill : (1) Cable anchorage ; (2) Filter ; (3) Electromagnetic pump ; (4) Ceramic tube ; (5) Heating wire ; (6) Stainless steel external tube ; (7) Weight ; (8) Nozzle ; (9) Tip.

On the surface, a transformer increases the supply voltage to reduce the line losses.

The drill is supplied by a 3.2 kVA generator, but it can be also supplied by a 2 kVA generator when the equipment has to be back-packed.

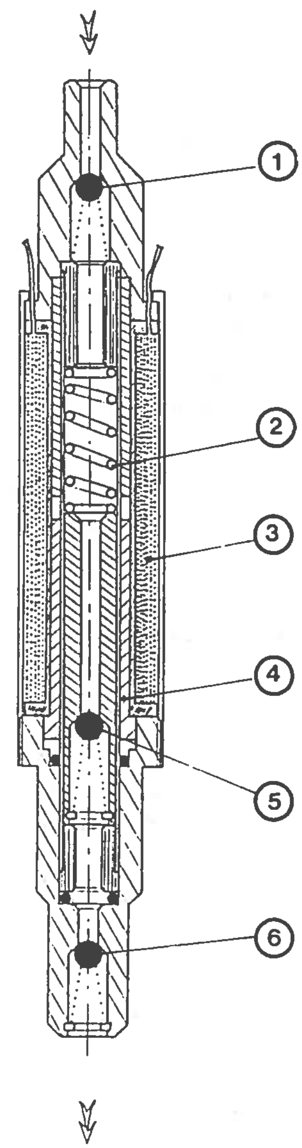

Fig. 2 Electromagnetic pump.
(1) Bottom valve ; (2) Pumping spring ; (3) Coil ; (4) Piston forming magnetic core ; (5) Priming valve ; (6) Delivery valve.

TECHNICAL CONSIDERATIONS

In temperate glaciers, the drilling rate of Electrochaude depends on several parameters, predominently :

- the heating power
- the nozzle shape
- the water jet pressure. This pressure is adjusted by the nozzle hole diameter.

At the Mer de Glace glacier, the maximum drilling rate was obtained with the smallest nozzle hole, in spite of a low water flow rate. This was due to the fairly high jet pressure.

ELECTRICAL SUPPLY (Fig. 3)

The electrical supply for both the pump and the heating element is arranged in series. Then we avoid problems due to power shortages in the pump coil. We need also a second diode to get the two waves of current in the heating element.

In order to protect the pump, a bimetallic switch is also mounted in series in case of lack of water.

HOLE QUALITY

Both the verticality and the regularity of the hole depend on the care of the driller who controls wether the drill is suspended or not by holding the cable. Initially, water was sucked up just above the nozzle and the drill recovered a few part of solid debris in the space between the ceramic tube and the external tube. This space was replaced by a thick stainless steel tube to increase the drill weight.

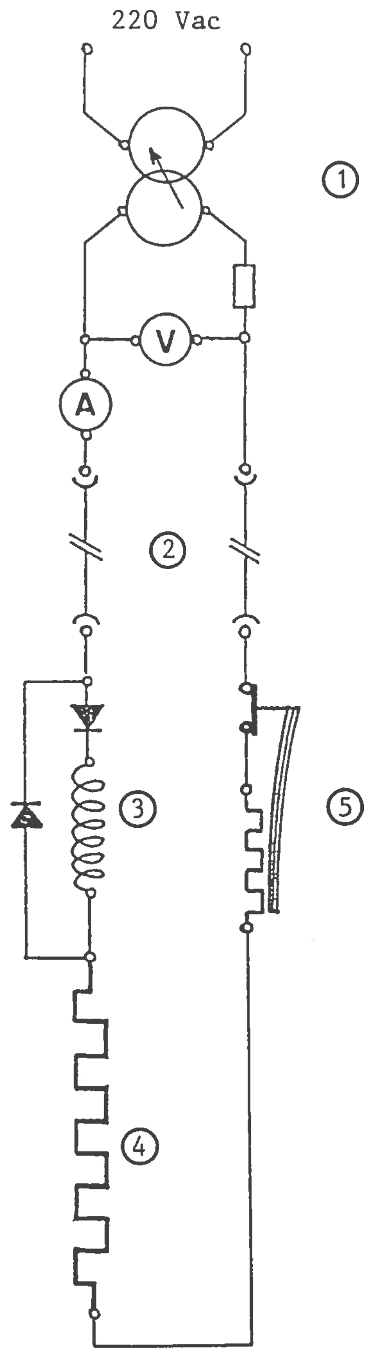

Fig. 3 Electrical diagram.
(1) Transformer ; (2) Cable ; (3) Pump coil ; (4) Heating element ;
(5) Bimetallic switch.

RELIABILITY

The main causes of malfunction were electrical shortage and spring failure in the pump. Both these problems were eventually overcome.

In the first version, all the elements (electrical connection, filter, pump and ceramic tube) were cased in the external tube and to fix the drill, it was necessary to pull out all the whole assembly. Now the pump can be changed without dismantling the drill. Problems of shortages in the connection were solved by two small plugs and a separate mechanical anchorage of the cable.

HOLE STARTING

The Electrochaude system can work only completely immersed in water. We have used both the steam drill and the hot point drill to bore through the snow and to start the two first meters in the ice. When the glacier surface is "dirty", the hot point drill loses its efficiency. Moreover, when it is used in snow or porous firn, it cannot work at full power. The steam drill is in this case a better starting drill.

In order to simplify hole starting, we have tested successfully a modified system using the Electrochaude drill, in which the pump is on the surface of the glacier and immersed in a water vessel. The drill is supplied by water through a rubber hose 25 m long and then heated in the ceramic tube. An electrical cable which runs along the rubber hose supplies the heating element.

FIELD EXPERIENCE

The drill was used to bore more than 1500 m of holes in temperate glaciers, but also in moderately cold glaciers such as Austfonna

Ice Cap, Svalbard (Spitzbergen). In this case, drilling needs the use of antifreeze.

CONCLUSION

This compact drill facility has proved its effectiveness. It is easily transported and able to drill in ice containing small rock debris.

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BORE HOLE MEASUREMENTS

ELECTRONIC INSTRUMENTATION USED IN BOREHOLE SURVEYING

by

J.R. Kelty and B.L. Hansen
Polar Ice Coring Office
University of Nebraska
Lincoln, Nebraska 68588-0640, U.S.A.

ABSTRACT

A directional survey of a borehole is based upon a series of measurements of an azimuth angle and an inclination angle made at successive stations along the borehole where the distance between the stations is accurately known. The measurements are made using a survey instrument containing two servo accelerometers, acting as inclinometers, a compass and the requisite instrumentation. The directional survey can be supplemented with temperature, diameter, pressure and other data. The electronic data acquisition package (DAP) designed and built in the University of Nebraska-Lincoln Physics Department Electronic Shop was first successfully used to log the Dye 3 Greenland borehole on June 7, 1986.

Two different survey tools are described, one using an Aanderaa Instruments compass and the other, three fluxgates arranged to measure magnetic field strength in mutually orthogonal directions, thus acting as a compass. In addition, two methods of powering the instrument, by battery and from a surface power supply, are described. The DAP uses a microprocessor which performs the data acquisition and control functions. The DAP data stream can include input from hole diameter, borehole fluid pressure, temperature and other functions in addition to that from the inclination and azimuth sensors. Caliper release is an example of a control function. Examples of the data sampling techniques, filtering and averaging, calibration of the electronics and sensors, and error analysis are given in detail. A modem circuit is used to transmit data to the surface, thus requiring only a coaxial cable for use in the logging. A BASIC program and Spreadsheet program used with a Portable PC computer for storing the logged data are discussed with numerical examples of the calculations required in borehole logging position determination.

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INTRODUCTION

Borehole directional survey equipment has been described by Gundestrup and Hansen (1) as used for the surveying of the borehole at Dye 3, south Greenland (2). Outputs from a compass, two servo inclinometers, and a thermistor were measured at the surface using a high accuracy digital multimeter and a rotary selector switch. In 1986 the Polar Ice Coring Office (PICO) survey tool was modified to include a battery powered microprocessor along with the original inclination and azimuth sensors used in previous surveys. This new electronic data acquisition package (DAP), designed and built in the University of Nebraska-Lincoln Physics Department, was first successfully used to log the DYE 3 Greenland borehole on June 7, 1986 and has since been used at DYE 3 in 1987 and at Byrd Station, Antarctica in January, 1988.

Inclination

The tilt or inclination angle of the survey tool is necessary in determining the tool position in a directional borehole survey. Several devices have been used to measure the inclination with respect to the vertical gravitational axis including single and multiple shot camera and plumb bob devices (3) (4). The PICO tool uses Schaevitz Servo Inclinometers (5), model LSRP-14.5°, purchased in pairs calibrated at -30°C (-22°F) and compensated for operation over the temperature range of 0°C (32°F) to -55°C (-67°F). The connections are solder pins and the units are stackable cylinders measuring 1.60 inches high and 1.43 inches in diameter. The solid-state electronics and servo sensor are totally enclosed within these sealed housings. Operated from a DC source, the output is an analog DC signal directly proportional to the sine of the angle of the tilt. In the level (horizontal) position, the DC output is zero. When tilted in one direction, the inclinometer output is 0 to +5V DC (14.5° tilt from the vertical) and when tilted the opposite direction the output is 0 to -5V DC (-14.5°). Two inclinometers are stacked with perpendicular tilt lines to give an inclination angle with respect to gravity vertical and a tilt direction referenced to the tool compass.

Azimuth

Azimuth is measured with a magnetic Aanderaa Compass model 1248 which has an allowable tilt of 12° and an accuracy of better than ± 2° (6). The compass was specially purchased unpotted and then gimbal-mounted with a range of 27° so that at inclinations of 0° to 30° the compass is horizontal. The 0° reading of the compass is aligned precisely with the inclinometers so that the tool rotation relative to magnetic north can be determined.

The Aanderaa compass acts as a potentiometer (resistance is 2 K-Ohm) with the compass needle as the wiper. The heading is determined by reading a ratio of the wiper voltage to the total potentiometer voltage when the needle is clamped steady. Thus the compass ratio is directly proportional to the rotation of the tool with respect to magnetic north and does not depend on the DC source across the potentiometer to remain constant over the entire hole survey. A wait of several seconds is required at each measurement level to allow the compass needle to settle from the tool motion in the hole.

DAP (Data-Acquisition Package)

The DAP is built using INTEL compatible CMOS 8085 microprocessor system integrated circuits (7). See Figure 1. The 8085 microprocessor is an 8-bit device that uses a multiplexed address-data bus scheme. The 8155 RAM-I/O device directly interfaces to this microprocessor and provides digital ports to activate the analog multiplexer, relays, various setup switches, and the cable slack switch. The 256 bytes of RAM memory in the 8155 chip is sufficient for the DAP since the data is averaged and stored as it is accumulated. An 8K byte 2764 EPROM provides the firmware used to acquire,

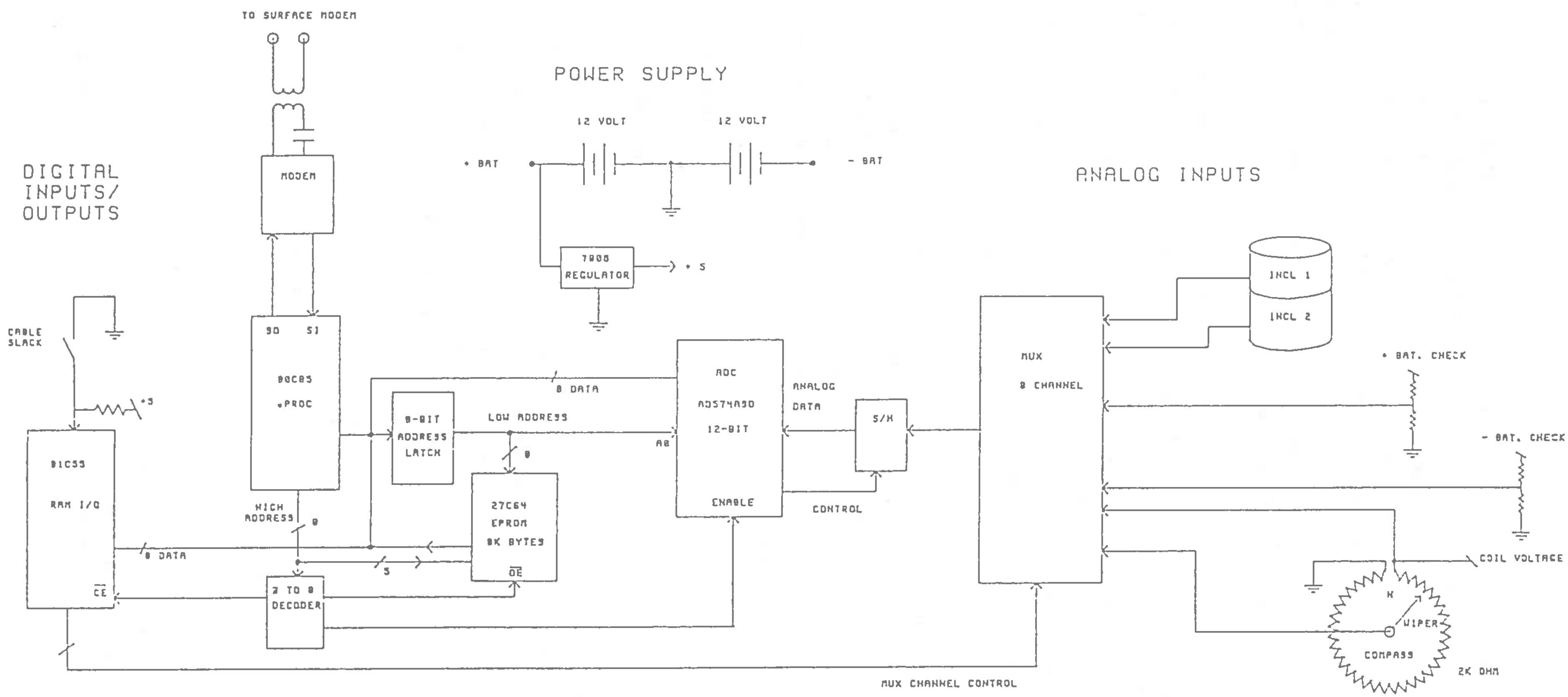

FIGURE 1. BLOCK DIAGRAM OF PICO LOGGING TOOL ELECTRONICS.

manipulate, and transmit data when requested by the surface computer.
Data is received and transmitted through serial in and out lines on the 8085 processor with a software bit detection scheme, eliminating the need for a separate UART type chip. The data is communicated to the surface via a transformer coupled 300 BAUD modem.

Data is accumulated by the DAP using an Analog Devices AD574AS 12-bit analog to digital converter (ADC) (8). The suffix AS is specified for -55°C to +125°C operating temperature range. The ADC is packaged in a 28-pin hermetically-sealed ceramic DIP and interfaces to the 8085 processor with an 8-bit path and an external address-bus buffer (that is shared with the EPROM). To insure that the signal to be measured remains stationary during the conversion time (about 25 microseconds) a sample and hold (S/H) circuit is used. The input signals are selected with an eight input multiplexer (MUX).

Software

The DAP is designed to be used with a 300 baud modem at the surface and some sort of RS-232 receiving device. The receiver could be a simple terminal, a speech synthesizer, or just a printer, but is usually an IBM compatible computer with a COM port available. With BASIC the data is read from the DAP with an OPEN COM statement and the INPUT command. The DAP is triggered by sending any character from the PC with a PRINT command. All characters are transmitted in ASCII, 7 bit, even parity, with 1 stop bit, at 300 BAUD and no handshaking is recognized.

Since the time required to position the tool at a given depth is longer then the acquisition time, the speed of a BASIC program is adequate. The DAP firmware (program in EPROM in the tool) sends a HEX data dump that is converted to variable values with a few simple lines of BASIC at the surface computer. A rather lengthy BASIC program has evolved which includes disk save and retrieve routines and other functions are handy in the field.

All of the transmitted raw data from the DAP is stored on floppy or fixed disk and a hardcopy is made as each point of the survey is taken. A small uninterruptable power supply (UPS) system is normally used in the event of a generator failure so that files may be properly closed and the PC turned off until after the generator is restarted.

The X, Y, and Z survey coordinates are calculated from knowing the inclination and the azimuth and the length of the cable paid out, which is either read from a serial device on the winch or entered by hand at each stopping station. See Figure 2. Data sent from the DAP becomes BASIC variables. The inclinometer voltages V1 and V2 are converted to the angle of inclination (I) tilted in a quadrant of the tool horizontal coordinate system. The azimuth AZ is the compass heading which is determined from the compass ratio R and the tool rotation AA in the hole. The distance the tool has traveled since the last point is S and the present X, Y, and Z coordinates are then calculated from the previous X, Y, and Z values.

Data Acquisition

Both digital and analog data is sampled by the DAP. The slack switch is an example of taking digital data, in this case a simple switch close. If the switch is closed, a bit on the 8155 I/O chip is pulled low and the DAP sends a "0" indicating that the cable has gone slack (the tool is at the bottom of the hole for example). If the switch is open, the bit is pulled high and the DAP returns a "1" to the surface receiver (as when the tool is hanging from the tower or is free in the hole).

Most of the DAP data is analog. The analog voltages are sampled with the AD574ASD analog to digital voltage converter through a multiplexer and sample and hold circuit. The devices to be read are the resistor networks indicating battery voltage, the compass ratio, and the inclinometer voltages, giving a total of 6 voltages to be measured. Since the compass requires a few seconds of settling time for the needle movement, the batteries and inclinometers are read first. A routine was designed that first selects the input voltage to be measured through the MUX, and then averages 4096 samples from the A/D converter. This may seem like a lot of samples but takes only 1 second per channel. Since the signals measured have noise that is greater then the bit resolution of the ADC (noise greater then 4.88 mV), the averaging helps to increase the resolution from the ADC 12-bits to an equivalent of about a 13.5-bit result (better then 1 part in 10000 or the equivalent of a 4-1/2 digit voltmeter). By the time the compass is to be read, 4 seconds have passed and the needle is hopefully pointing near magnetic north without oscillation and the compass ratio is read. The total acquisition time is about 6 seconds plus the time required to actually transmit the data, which is about 2 seconds. So for each hole station measurement, it takes about 8 seconds to obtain the position data once the tool has been placed.

```
810 'GEOMETRIC CALCULATIONS
830 V1(J%)=INCL1:V2(J%)=INCL2      'VOLTAGES FROM INCLINOMETERS
840 S1=(V1(J%)+.003)/19.994        'OFFSET AND SPAN CORRECTIONS
850 S2=(V2(J%)+.053)/19.966
860 AB=ATN(S2/S1) * 180/PI         'TO FIND DIRECTION OF TILT
870 IF S1 < 0 AND S2 < 0 THEN AA=AB+180   'TOOL QUADRANT III
880 IF S1 < 0 AND S2 > 0 THEN AA=AB+180   'IV
890 IF S1 > 0 AND S2 > 0 THEN AA=AB       'I
900 IF S1 > 0 AND S2 < 0 THEN AA=AB+360   'II
910 I(J%) = FNB(SQR(S1^2 + S2^2))   'INCLINATION ANGLE
    FNB IS ARCSIN DEFINED EARLIER AS FNB(X)=ATN(X/SQR(1-X^2))
920 R=COMP(J%)                            'COMPASS RATIO
930 AC = .03 + (360.1 * R)                'OFFSET AND SPAN CORRECTION
940 IF AA < AC THEN AZ(J%) = (( AA + 360 - AC ) * PI / 180 )
950 IF AA > AC THEN AZ(J%) = (( AA - AC ) * PI / 180 )
960 AA(J%)=AA   'INDICATES TOOL ROTATION     AZ IS THE AZIMUTH
970 S = DEPTH(J%) - DEPTH(J% - 1)   'CABLE LENGTH PAID OUT
980 XLOC(J%) = XLOC(J%-1) + S/2 *   'X,Y,Z COORDINATES
((SIN(I(J%-1))*SIN(AZ(J%-1)))+(SIN(I(J%))*SIN(AZ(J%))))
990 YLOC(J%) = YLOC(J%-1) + S/2 *
((SIN(I(J%-1))*COS(AZ(J%-1)))+(SIN(I(J%))*COS(AZ(J%))))
1000 ZLOC(J%) = ZLOC(J%-1) + S/2 * (COS(I(J%-1))+COS(I(J%)))
```

Figure 2 - Calculating hole coordinates from survey data in a BASIC program.

A New DAP Design

A new survey tool DAP has been constructed and is currently under test. The new tool takes its power from the surface instead of batteries and uses a fluxgate compass instead of an Aanderaa Instruments magnetic needle type compass. As with the original PICO tool, servo inclinometers are used to measure the tilt respect to the gravitational axis. There are major changes in the DAP firmware and a spreadsheet program is used in the surface computer to dramatically improve data observation in the field as the hole is logged.

Fluxgate Compass

In an effort to improve the azimuth readings, a fluxgate compass has been designed and is under test. Three orthogonally-oriented fluxgate sensors have been mounted in a fixture that matches an X and Y gate with the two inclinometer tilt lines and a Z gate with the tool vertical axis. The DAP reads three voltages proportional to the magnetic field sensed by each gate, and the surface computer normalizes these to give the normalized X, Y and Z magnetic components of the earth's field with respect to the tool orientation in the hole. Once again, the inclinometers are used to find the tilt and tool rotation, and the azimuth is calculated from both the inclinometer and compass values. The azimuth is given by the equation

$$\psi = \tan^{-1}\left[\frac{-(B_x \cdot \sin\phi + B_y \cdot \cos\phi)}{\cos\theta \cdot (B_x \cdot \cos\phi - B_y \cdot \sin\phi) + B_z \cdot \sin\theta}\right]$$

where B_x, B_y, and B_z are the normalized magnetic field components, Θ is the inclination angle, ϕ is the highside angle (the tool rotation), and Ψ is the azimuth angle (9).

The fluxgate elements used are type LFG-A14 from Kelvin Hughes (10). These devices are constructed with excitation coils wound along lengths of high permeability wire. The excitation coils are then positioned side by side within a bobbin onto which a secondary sense coil is wound. These input coils are wired opposite and balanced so that with no external magnetic field present, the output secondary shows no output voltage. An external magnetic field lined along the axis of the element produces a voltage in the sense winding as one excitation coil is assisted and the other opposed. The output is proportional to the field and reverses polarity when the fluxgate element axis is inverted. The excitation frequency is set to 400 HZ and the resultant output pulse frequency is 800 HZ. This pulse is filtered and integrated to give a DC voltage output that is proportional to the magnetic field intensity (11).

Battery vs. Surface Power Supply Design

The use of batteries to power the DAP and sensors seemed at first very desirable. Batteries are DC with no ripple voltages and for the DAP design require no regulation except for the 5 volt supply. The voltages on the batteries are monitored with a simple voltage divider network so that the DAP can measure the battery voltage (the ADC has a maximum positive or negative input of 10 V DC). The cells connected for the positive 12 V DC always discharge quicker than the negative cells due to the imbalance caused by the 5 V DC requirement. Separate cells for the 5 V DC could be used, but the size and weight of the tool would be increased. As it is, the battery section is the longest and heaviest portion of the tool, containing twelve Gates lead acid batteries (type 0800-0004, X Cell, 2.0 Volt, 5.0 Ah) (12). The charge time of the batteries is typically overnight. Two chargers are used so that the negative and positive sides charge independently as required by their state of discharge. The chargers are wired so that they share a common ground and make it easy to apply a voltmeter to either the positive or negative side with respect to the common, or measure the total charge of the entire battery string from positive to negative. A good state of charge is better than 28 V DC. The cells drain to about 23.5 V DC after about 8 hours of logging (the imbalance gives about -12 and +11.5 V DC typically).

In an effort to make the tool smaller and weigh less, a surface supply has been designed, but has yet to be tested in the field. A 5 V DC regulator is used in the same way as with the battery supply and again an imbalance in the positive and negative voltage sources exists. Since the supply from the surface is abundant, a resistor is placed on the negative side of the DAP supply to help balance the load. Positive and negative 15 V DC is used instead of 12 volts since there is no space limitation as with additional battery cells. Modems at the surface and in the DAP are connected as before through audio transformers, but now the transformers must be able to handle the current supplied to the DAP circuit in addition to the audio signal. Two 18 Volt zener diodes are used to provide adequate input to the positive and negative 15 V DC regulators and are used to "take up the slack" in current that the resistor and regulators use from the unregulated DC surface source. If the zener diodes were not present, current pulses (and thus voltage pulses) appear at the audio transformers when the fluxgate cells are excited. Unfortunately, the fluxgates are excited at a rate of 800 Hz which is close enough to the modem frequencies that the transmission of spurious data is created during fluxgate activity. The installation of the zener diodes reduces the line pulses to where the modem devices successfully filter out the unwanted noise created by the fluxgate drive circuitry. Since the cable is usually long (over 2000 meters), the resistance of the wire causes a voltage drop, usually greater than the voltage needed by the tool itself. A surface supply capable of approximately 175 V DC and 2 amperes was built with the possible alternate use as a reamer motor supply. Ripple on the surface supply is approximately 3 % of the output voltage, which is easily handled by the DAP regulators.

Another design under consideration uses a 9 V DC zener diode and voltage converter modules to obtain ± 5 and ± 15 V DC supplies. Tests have not been completed on this power supply design, but the main advantages are one zener at a significantly lower voltage (thus requiring a smaller, safer surface supply, may be even solar panels) and no imbalance resistor to compensate for the 5 V DC drain on the positive supply side. This design might also prove good for use with batteries since only parallel 9 V DC cells are required.

New Sensor Additions

A caliper could be added to the PICO survey tool. The DAP could receive and decode a special character or message from the surface computer to trigger a caliper arm release solenoid. A DC-LVDT is available from Schaevitz Engineering that operates from a ± 15 V DC power source and has a ± 10 V DC output. This position transducer has been used with a separate PICO caliper tool using the survey tool battery pack and a surface voltmeter. The output voltage from the linear variable differential transducer (LVDT) could be connected to an unused DAP MUX channel and the hole diameter data sent as part of the data stream. Other calipers are described (1) (13) (14) and the electronic additions are small in comparison to the mechanical design required.

A pressure transducer is also easy to add to the DAP system and would be a desirable addition as part of a more complete PICO survey tool. The Paroscientific Digiquartz Pressure Transducer (15) has a digital frequency output and requires a single DC power source. A frequency-to-voltage converter or gated counter could provide the necessary interface to the DAP system.

CONCLUSION

The addition of the DAP to the PICO survey tool has greatly increased its adaptability to various transducers and eased the task of data acquisition in a harsh environment. Use of packaged software (such as spreadsheet programs) allows preliminary observations in the field so that decisions about the quality of the data taken can be made onsite. The versatility of a microprocessor-controlled survey tool greatly enhances the science of borehole logging.

ACKNOWLEDGEMENTS

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ICE CORE QUALITY

ASSESSING THE QUALITY OF THERMALLY DRILLED DEEP ANTARCTIC ICE CORES FOR TRACE ELEMENTS ANALYSIS

by

Boutron C.F.[1,2], Patterson C.C.[2] and Barkov N.I.[3]

[1] Laboratoire de Glaciologie et Géophysique de l'Environnement du C.N.R.S., Domaine Universitaire, B.P. 96, 38402 Saint-Martin d'Hères cédex, France.

[2] Division of Geological and Planetary Sciences 170-25, California Institute of Technology, Pasadena, California 91125, U.S.A.

[3] Arctic and Antarctic Research Institute, UL Beringa 38, 199226 Leningrad, U.S.S.R.

ABSTRACT

Concentrations of Pb, Zn, Na, Mg, K, Ca, Fe and Al have been measured in successive veneers of ice mechanically chiselled progressing from the outside to the very center of various sections of the Dome C and Vostok deep Antarctic ice cores. Mean elemental contamination present in the outside layer of the cores was found to range from 0.3 ng/g (Al) up to 20 ng/g (Na) for the Dome C core, and from 5 ng/g (Al) up to 290 ng/g (Zn) for the Vostok core. Contrasting outside - inside curves were observed for the various elements. Plateaus of concentrations were obtained in the inner parts of the cores sections in all cases for Na and Mg, and in most cases for K, Ca, Fe and Al. For Pb and Zn, on the other hand, plateaus were observed only for part of the sections, which confirms that for these two heavy metals it is of utmost importance to study in details the variations of the concentrations from the outside to the inside of each core section if reliable data are to be obtained.

1 - INTRODUCTION

During the past 25 years, extensive efforts have been devoted to reconstruct the past variations of the composition of the earth's atmosphere during the last 150,000 years through the analysis of various elements or compounds in deep Antarctic or Greenland ice cores. Among the elements or compounds which have been investigated are major sea derived or soil derived elements such as Na, Cl, Mg, K, Ca and Al (see for instance Cragin et al. (1977), Petit et al. (1981) and De Angelis et al. (1987), sulfate and nitrate (see for instance Herron and Langway (1985), Legrand and Delmas (1988) and Legrand et al. (1988) and heavy metals such as Pb, Cu, Zn and Cd (see for instance Boutron and Patterson (1986), Boutron et al. (1987) and Batifol et al. (1989). Unfortunately, deep ice cores are always contaminated on their outside during drilling, field processing, transportation and storage. The severity of this outside contamination varies greatly from one core to another and from one element or compound to another. It is especially high for cores drilled in fluid filled holes. This contamination will penetrate more or less deeply into the ice cores, depending on numerous factors.

If reliable data are to be obtained from the analysis of these cores, it will be first of utmost importance to study in full details for each element or compound how deep contamination has intruded into the cores in order to determine whether the inner parts of the cores are free of contamination or not and are therefore suitable for elemental analysis. It will then be necessary to develop ultraclean laboratory procedures to get these inner parts of the cores without transferring outside contamination to these inner parts.

We present here comprehensive data on the contamination characteristics of various sections of two thermally drilled deep Antarctic ice cores. These data were obtained by investigating the variations of the concentrations of Pb, Zn, Na, Mg, K, Ca, Fe and Al from the outside to the inside of these sections.

2 - EXPERIMENTAL

2.1 - Description of the core sections

We have studied 10 sections of the 905 m Dome C core (depths ranging from 172.8 to 796.9 m) and six sections of the 2,083 m Vostok core (depths ranging from 499.1 to 2,026.3 m). The Dome C core was thermally drilled in a dry hole (Lorius and Donnou, 1978 ; Lorius et al, 1979). The Vostok core was thermally drilled in hole filled with kerosene and freon (Kudryashov et al., 1984 a, b ; Barkov et al., 1988). Each section was 15-30 cm in length. The diameter was 10.5 cm for all the Dome C sections, 10.8 cm for the Vostok sections from the surface down to 1,500 m, and 9.1 cm for the Vostok sections deeper than 1,500 m. Full sections were available for the present study, except a shallow-chord shaving which was cut in the field with a band saw for continuous measurements of oxygen and hydrogen isotopes. No special precautions were taken for the handling of these sections in the field, which means that they have been in contact with leather or woollen gloves and with wooden or plastic gutters, and that they have been exposed to contaminated air in the drilling trench before being sealed in non acid cleaned polyethylene bags.

2.2 - Mechanical chiselling of the core sections

The chiselling took place inside a cooled double walled conventional polyethylene tray flushed with cooled nitrogen (Boutron and Patterson, 1983) placed inside the ultraclean Patterson's laboratory (Patterson and Settle, 1976) at California Institute of Technology (C.I.T.). We mechanically chiselled 4 to 6 successive veneers of ice in progression from the outside to the interior of each core section, using stainless steel chisels. The ends of the ice sections were also shaved. Each veneer layer was approximately 6-10 mm thick, depending upon the number of veneer layers. The remaining inner core obtained after the chiselling was completed, was usually 3 to 4 cm in diameter and 10-20 cm in length.

Sophisticated ultraclean procedures were used to prevent entrainment of the huge contamination existing on the outside of the core sections to the successive veneer layers and to the final inner core. These procedures were similar to those previously described in full details by Boutron and Patterson (1983). Various improvements were however effected. These improvements included the use of several stainless steel chisels instead of a single chisel, which allowed better cleaning of each chisel between its use for different veneer layers. Conventional polyethylene collection trays and 1 liter beakers were used for the collection of the ice chips and the melting of each veneer layer or inner core instead of quartz trays and beakers in the earlier study. Also, the cleaning procedures were improved : the second acid bath was 0.1 % ultrapure HNO_3 from U.S. National Bureau of Standards, instead of 1 % electronic grade HNO_3 from John Frederic Smith.

2.3 - Analytical procedures

Each veneer layer and each inner core were analysed separately. They were allowed to thaw overnight at room temperature in 1 liter conventional polyethylene beakers. Ultrapure HNO_3 from U.S. National Bureau of Standards was then added to make a 0.1 % HNO_3 solution. The solution was allowed to sit for 2 hours. About half of this solution was then analyzed for Pb by Thermal Ionization Isotope Dilution Mass Spectrometry (I.D.M.S.) at C.I.T.. The other half was transported frozen to the Laboratoire de Glaciologie et Géophysique de l'Environnement (L.G.G.E.), where a small sub-aliquot (about 2 ml) was analyzed for Zn, Na, Mg, K, Ca, Fe and Al by Graphite Furnace Atomic Absorption Spectrometry (F.A.A.S.) without preconcentration (multiple (up to 10) 50 µl injections were used for Zn). The analytical precision was better than 10 % for Na, Mg, K, Ca, Fe and Al. For Pb and Zn, it was better than 10 % for the high concentrations of the Last Glacial Maximum, but it was up to 50 % for the very low Holocene concentrations.

2.4 - Chiselling blanks

Contamination introduced by the mechanical chiselling was directly measured using an artificial ice core of frozen ultrapure water. This ice core (diameter : 10 cm ; length : 20 cm) was prepared by freezing about 1.6 l of C.I.T. ultrapure quartz distilled water (Q.D.W.) of known composition (Pb : 0.16 pg/g ; Zn : 2.5 pg/g; Na : 40 pg/g ; Mg : < 3 pg/g ; K : < 60 pg/g ; Ca : < 10 pg/g ; Fe : < 15 pg/g ; Al : < 20 pg/g) in an ultraclean 2 liters conventional polyethylene bottle. The bottle was then cut using an acid-cleaned stainless steel scalpel, and the artificial ice core so obtained was chiselled according to the procedure described in section 2.2. One of the veneer layers and the inner core were then analyzed separately, thus allowing to determine how much Pb, Zn, Na, Mg, K, Ca, Fe and Al were added by the chiselling procedure.

The chiselling blanks were found to vary greatly from one element to another, Table 1. For the inner core, they range from 0.05 ng for Pb up to 25 ng for Al. Surprisingly, very low values were obtained for Fe (≤ 7.5 ng), despite the fact that a stainless steel chisel was used. When compared with the typical elemental content of Antarctic ice, Table 1, the chiselling blanks are found to be extremely small for Na, Mg, K, Ca and Fe. For Pb, Zn and Al however, the chiselling blanks can be up to 75 % of the elemental content of Antarctic inside veneer layers or inner cores.

3 - CONTAMINATION CHARACTERISTICS OF THE DOME C AND VOSTOK CORES

3.1 - Contamination on the outside of the core sections

Table 2 gives the concentrations measured in the first (outside) veneer layer and in the

Element	ng introduced into the veneer layer [a]	ng intoduced into the inner core [b]	ng in a typical 200g veneer layer or inner core Holocene ice [c]	LGM ice [d]
Pb	0.05	0.05	0.13	3
Zn	1.5	1.0	1.7	10
Na	45	15	3500	17000
Mg	8.5	5	500	3300
K	10	10	400	2800
Ca	<5	<5	230	5700
Fe	<7.5	<7.5	180	5200
Al	190	25	290	8500

[a] 375 g ice veneer made with 28 strokes of the stainless steel chisel - [b] 515 g inner core - [c] Calculated from mean concentrations measured in the inner cores of sections 172.8 m, 300.6 m, 373.9 m and 451.9 m of the Dome C core - [d] Calculated from mean concentrations measured in the inner cores 527.2 m, 545.1 m, 602.2 m, 658.2 m., 670.5 m and 704.2 m of the Dome C core.

Table 1 - Comparison of chiselling blanks (measured by processing an artificial ice core of known composition) with typical trace elements content of Holocene and Last Glacial Maximum (LGM) Dome C ice.

Core section	Pb pg/g	Zn pg/g	Na ng/g	Mg ng/g	K ng/g	Ca ng/g	Fe ng/g	Al ng/g
Dome C								
172.8	2320	8600	42	4.7	35	10	18	7.3
	(0.76)	(6.1)	(13)	(1.9)	(1.5)	(1.0)	(0.48)	(0.95)
300.6	720	1700	29	3.1	15	3.3	5.4	4.0
	(0.47)	(9.3)	(16)	(2.45)	(2.6)	(1.2)	(1.1)	(1.6)
373.9	772	4020	47	2.8	40	7.9	7.7	4.3
	(0.94)	(4.9)	(7.5)	(1.05)	(1.5)	(0.48)	(0.48)	(1.4)
451.9	646	1300	47	6.6	13	5.2	4.3	3.1
	(0.43)	(6.0)	(34)	(5.1)	(2.5)	(2.0)	(1.5)	(1.9)
500.5	668	1840	68	11	24	11	10	7.1
	(3.8)	(16)	(53)	(8.4)	(5.2)	(6.2)	(6.8)	(8.0)
545.1	340	1830	83	18	30	37	21	25
	(10.2)	(32)	(63)	(16)	(9.0)	(23)	(17)	(21)
602.2	1030	4360	111	22	19	27	18	17
	(11.4)	(40)	(102)	(22)	(14)	(21)	(20)	(37)
670.5	707	2080	92	27	17	60	38	44
	(29.3)	(63)	(75)	(22)	(12)	(26)	(31)	(38)
775.7	45000	37600	128	17	46	47	106	39
	(7.2)	(10.5)	(55)	(10)	(4.2)	(7.0)	(4.3)	(6.0)
796.9	1100	4000	80	11	19	7.5	9.0	5.6
	(1.2)	(7.8)	(58)	(10)	(4.1)	(4.7)	(2.9)	(4.4)
Vostok								
499.1	20600	99000	140	35	61	180	108	35
	(38)	(33)	(92)	(19)	(10)	(18)	(9.7)	(24)
851.6	-	400000	76	16	34	39	39	29
	(3.1)	(14)	(65)	(11)	(6.3)	(8.9)	(6.6)	(32)
1425.3	20000	300000	82	20	59	200	89	38
	(2.4)	(3.8)	(34)	(6.4)	(3.4)	(5.0)	(2.8)	(7.1)
1775.4	-	220000	52	16	51	56	135	25
	(2.6)	(3.0)	(15)	(2.4)	(1.7)	(2.4)	(1.3)	(3.6)
1850.4	15700	400000	56	11	49	71	114	10
	(10.6)	(12.5)	(8.3)	(1.3)	(0.7)	(0.43)	(0.2)	(0.9)
2026.3	31400	300000	156	40	79	310	263	55
	(20)	(24)	(98)	(27)	(25)	(51)	(44)	(95)

Table 2 - Dome C and vostok deep Antarctic ice cores : comparison of concentrations measured in the first (outside) layer with concentrations measured in the inner core. For each section and each element, the upper value gives the concentration measured in the first layer, and the lower value (in brackets) gives the concentration measured in the inner core.

inner core for each of the Dome C and Vostok core sections. It must be emphasized that the first (outside) veneer layer was about 6 to 10 mm thick : the corresponding concentrations listed in Table 2 then represent mean concentrations over that thickness interval. The concentrations present on the very outside surface of the core sections were then probably much higher. Table 3 shows the mean concentration differences, C, between the first (outside) veneer layer and the inner core for the Dome C and Vostok cores. Since the inner core concentrations are in most cases close to the original concentrations in the ice, these C values represent the mean contamination which was present in the outside layer of the ice cores.

For the Dome C core, the C values range from 0.3 ng/g for Al up to 20 ng/g for Na. When compared with the mean original concentrations in the ice, the relative importance of this contamination changes considerably from one element to another : for Pb and Zn, it represents about 150 fold the original concentrations ; for K, about 4 fold ; for Al, about 1.05 fold. Especially for Fe, Al and Zn, part of this contamination is likely to originate from the various components of the thermal drill used at Dome C : the melting head (bare spiral resistance wire made out of a Fe - Cr - Al alloy), the Al head support, the stainless steel barred (FE, Cr, Ni, Mo), the galvanized steel cable (Fe, Zn) and the Al winch drum (Gillet et al, 1976 ; Lorius and Donnou, 1978). But another part of this contamination is probably added to the ice cores after they have been removed from the drill. This last contamination is thought to originate from the dust and gases present in the drilling trench, and from the dirtiness of the various items which contact the cores in the drilling trench (gutters into which the cores are placed for logging, bandsaw used to cut the continuous slice for oxygen and hydrogen isotopes measurements, gloves and clothes of the operators, polyethylene bags used to pack the cores...). These items are likely to have been contaminated by urban air during manufacturing and in the home laboratory, by the walls of the various cases in which they were packed during transportation to the field, by contaminated marine air in the holds of the supply ships, by exhaust gases and particles from aircrafts, caterpillar vehicles, field power generators... This contamination is then probably a very complicate blend of various components, including anthropogenic dust and gases, soil dust, seasalts... Finally, some contamination might have been added to the cores during transportation back to the home laboratory and during storage, especially when the polyethylene bags used for the packing of the core sections were not tightly sealed or were damaged.

For all the investigated elements, the C values measured for the Vostok core are higher than those obtained for the Dome C core, Table 3. The effect is especially pronounced for Zn (2 orders of magnitude difference between the Vostok and Dome C values) and for Pb, fe, Ca and Al (1 order of magnitude difference). It is rather small for Na and K. This stronger contamination of the outside of the Vostok core is probably mainly due to the fact that it was drilled in a fluid filled bore hole (Kudryashov et al, 1984 a, b). This fluid was a mixture of kerosene and freon (Barkov et al, 1988). Unfortunately, we have no direct data on the elemental content of this fluid. It is moreover unlikely that a

	Pb	Zn	Na	Mg	K	Ca	Fe	Al
Dome C [a]	0.92	3.3	20	1.9	18	9.3	5.6	0.3
Vostok	22	287	42	12	48	128	114	4.9

[a] Except section 775.7 m. This section was probably badly contaminated because of severe technical problems encountered with the drill near that depth.

Table 3 - Mean concentration differences, Δ C, between the first (outside) layer and the inner core for nine sections of the Dome C core and six sections of the Vostok core. All Δ C values are given in ng/g.

good prediction of this elemental content can be made from the few available data on the elemental content of kerosenes and freons from other parts of the world (see for instance Smith et al, 1975) since impurities in the Vostok fluid probably did not come only from the original liquids. Part of them were probably added to these liquids both from the walls of the containers, barrels and pipes during their transportation to Vostok and from the drill itself and its cable during drilling operations.

3.2 - Outside -inside variation profiles

As first proposed by Ng and Patterson (1981), the investigation of the variations of the elemental concentrations from the outside to the inside of each core section as a function of radius is an unique way to determine how deep outside contamination has penetrated into each core section. Continuous decrease of concentrations from the outside to the inside indicates that outside contamination has penetrated to the very center of the core section : the analysis of this very center will then allow to get only upper limits of the original elemental concentrations in the ice. On the other hand, if an unambiguous plateau of concentrations is observed for at least two consecutive inner layers, this clearly indicates that outside contamination has not penetrated to the central parts of the core section : the analysis of the inner layers for which a plateau is observed will then allow to get the original elemental concentrations in the ice, providing of course that satisfying blank corrections have been made for the chiselling and analytical procedures.

For Na and Mg, excellent plateaus of concentrations were observed for all the Dome C and Vostok sections, Table 4. In most cases, the plateau was reached from the second layer from the outside, as illustrated in Figure 1 a, b, which means that for Na and Mg, contamination did not penetrate beyond about 6 to 10 mm from the outside for most Dome C and Vostok core sections. For Na, the only two exceptions were for two Dome C sections (373.9 and 775.7 m), for which the plateau was reached only from the third layer from the outside (but the Na concentration for the second layer was only slightly higher than that in the third layer). For Mg, this last situation occured only for the 373.9 m Dome C section and for the 1,775.4 m Vostok section (but as for Na, the concentration in the second layer was only slightly higher than that in the third layer). For Mg, we even had two situations (Dome C 545.1 and 602.2 m, Figure 1 c) where the plateau started from the first layer (flat Mg concentration profile from the very outside to the center).

For K, Ca, Fe and Al, excellent plateaus of concentrations were obtained for most core sections, Table 4. However, for each of these elements, we did find a few core sections for which no plateau at all was obtained : Dome C 172.8 m for Fe and Al ; Dome C 373.9 m for Fe ; Dome C 775.7 m for K and Al ; Vostok 1,850.4 m for Ca and Fe. When a plateau was obtained, it started at variable distances from the outside of the cores : in a very few cases, it started from the first layer, as illustrated in Figure 2 a (flat concentration profile from the very outside to the center). In many cases, the plateau started from the second layer, Figure 2 b. Finally, in some cases, the plateau was obtained only for the two most central layers of the core, Figure 2 c. It is interesting to note that for a given core section, the situation was in many cases changing from one element to another. For instance, for Dome C 172.8 m, the plateau started from the second layer for Ca and from the fourth

Core Section	Pb	Zn	Na	Mg	K	Ca	Fe	Al
Dome C								
172.8	-	-	+	+	+	+	-	-
300.6	-	+	+	+	+	+	+	+
373.9	-	-	+	+	+	+	-	+
451.9	+	+	+	+	+	+	+	+
500.5	+	+	+	+	+	+	+	+
545.1	+	+	+	+	+	+	+	+
602.2	+	+	+	+	+	+	+	+
670.5	+	-	+	+	+	+	+	+
775.7	-	-	+	+	-	+	+	-
796.9	+	+	+	+	+	+	+	+
Vostok								
499.1	+	-	+	+	+	+	+	+
851.6	-	-	+	+	+	+	+	+
1425.3	-	-	+	+	+	+	+	+
1775.4	-	-	+	+	+	+	+	+
1850.4	-	-	+	+	+	-	-	+
2026.3	+	-	+	+	+	+	+	+

Table 4 - Investigation of the outside - inside variations of the concentrations of eight elements in various sections of the Dome C and Vostok cores. Symbol + indicates that a satisfying plateau of concentrations was obtained in the inner part of the core for at least two consecutive veneer layers. Symbol - indicates that no satisfying plateau was observed.

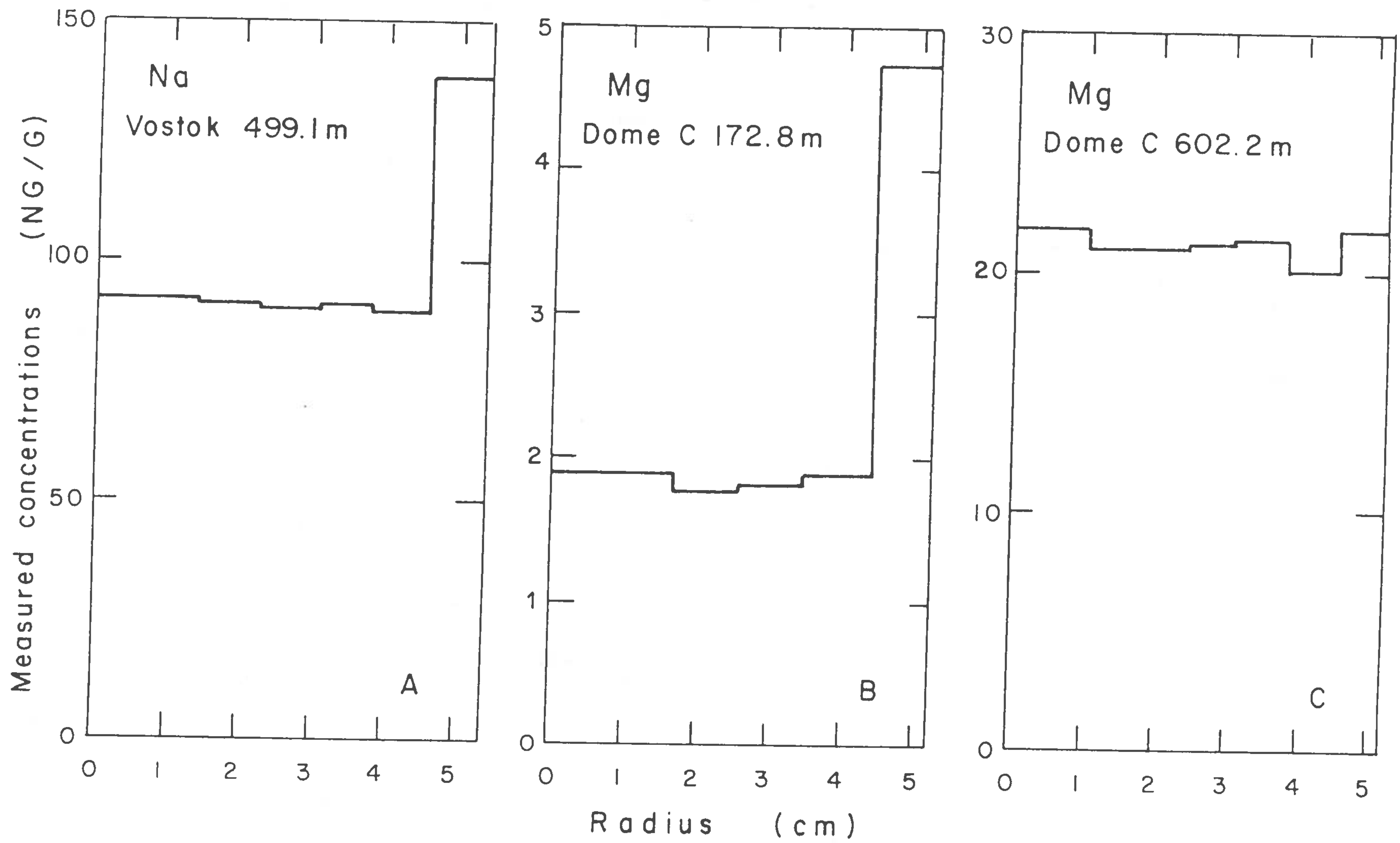

Figure 1 - Variations of elemental concentrations from the outside to the inside of three core sections as a function of radius. a) Na, Vostok 499.1 m. b) Mg, Dome C 172.8 m. c) Mg, Dome C 602.2 m.

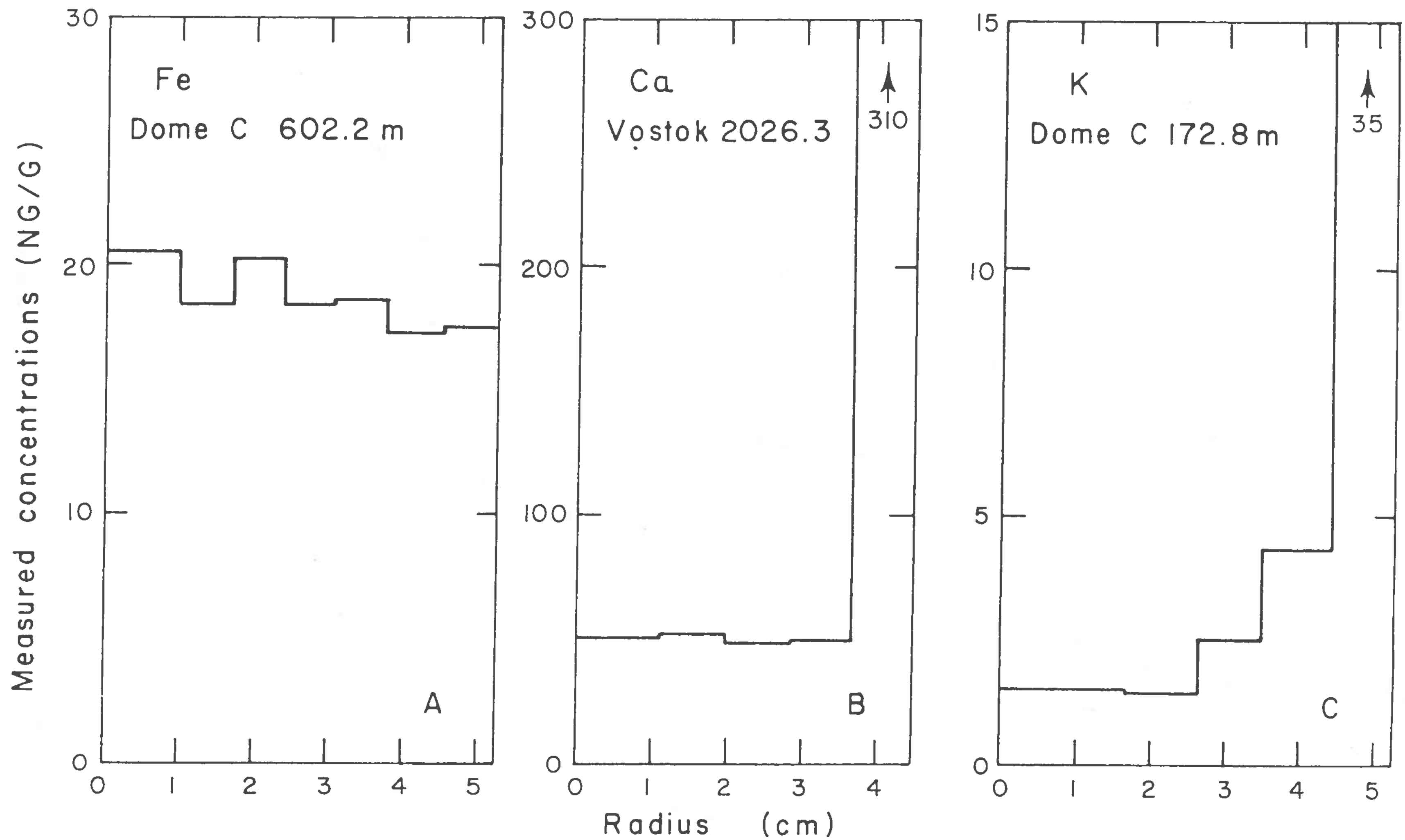

Figure 2 - Variations of elemental concentrations from the outside to the inside of three core sections as a function of radius. a) Fe, Dome C 602.2 m. b) Ca, Vostok 2,026.3 m. c) K, Dome C 172.8 m.

layer for K, and no plateau at all was obtained for Fe and Al.

Much more contrasting situations were observed for Pb and Zn, whose concentrations in Antarctic ice are several orders of magnitude lower than those of Na, Mg, K, Ca, Fe and Al (pg/g instead of ng/g level). For Pb, we found good plateaus for only six out of the ten Dome C core sections, and for only two out of the six Vostok sections, Table 4. For Zn, we also found good plateaus for six Dome C sections, but we did not get a plateau for any of the six Vostok sections, Table 4. When a plateau was obtained, it started at variable distances from the outside. In some cases, it started from the second layer, but in most cases was observed only for the most central layers of the cores. In some cases, Pb and Zn behaved similarly : for instance, a plateau was observed for both metals for Dome C 500.5 m, Figure 3 a ; and no plateau was obtained for both metals for Dome C 172.8 m, Figure 3 b. But in other cases, they behaved differently : for Dome C 300.6 m, a plateau was obtained for Zn, but not for Pb, Figure 4 a ; for Vostok 499.1 m, on the other hand, the opposite situation happened : no plateau was obtained for Zn, while a plateau was observed for Pb, Figure 4 b.

4 - CONCLUSIONS

Our results clearly indicate very contrasting situations for the eight elements investigated in the present study. For Na and Mg, our data suggest that outside contamination probably never penetrates beyond about 1-2 cm from the outside of the cores, both for Dome C and for Vostok : reliable Na and Mg values can then be obtained for both cores after discarding this outside part of the cores. For K, Ca, fe and Al, the situation is not so clear : if in most cases, reliable data can be obtained from the analysis of the inner parts of the cores, however the fraction of the core to be discarded is rather variable. Moreover, in some cases even the most central parts of the cores appear to be contaminated. Finally, for Pb and Zn, the situation appears to be much more complicated : for these two metals, our data confirm that it is mandatory to draw complete outside-inside concentration profiles for each section in order to get reliable data whose quality can be clearly assessed.

Our data are for eight elements only. It will be necessary in the near future to perform such detailed studies for various other elements or compounds. Such investigations will be especially interesting for heavy metals such as Cd, Cu, Ag, Hg, Bi and Ir, whose concentrations are at or below pg/g level. Only when detailed reliable outside-inside variation profiles have been obtained for these heavy metals will it be possible to get reliable data on their concentration changes in Antarctic ice cores in order to reconstruct their past pre-man natural fluxes.

Our data are for thermally drilled cores only. It will be necessary in the near future to perform similar detailed studies for electromechanically drilled ice or firn cores in order to determine the contamination characteristics of such cores.

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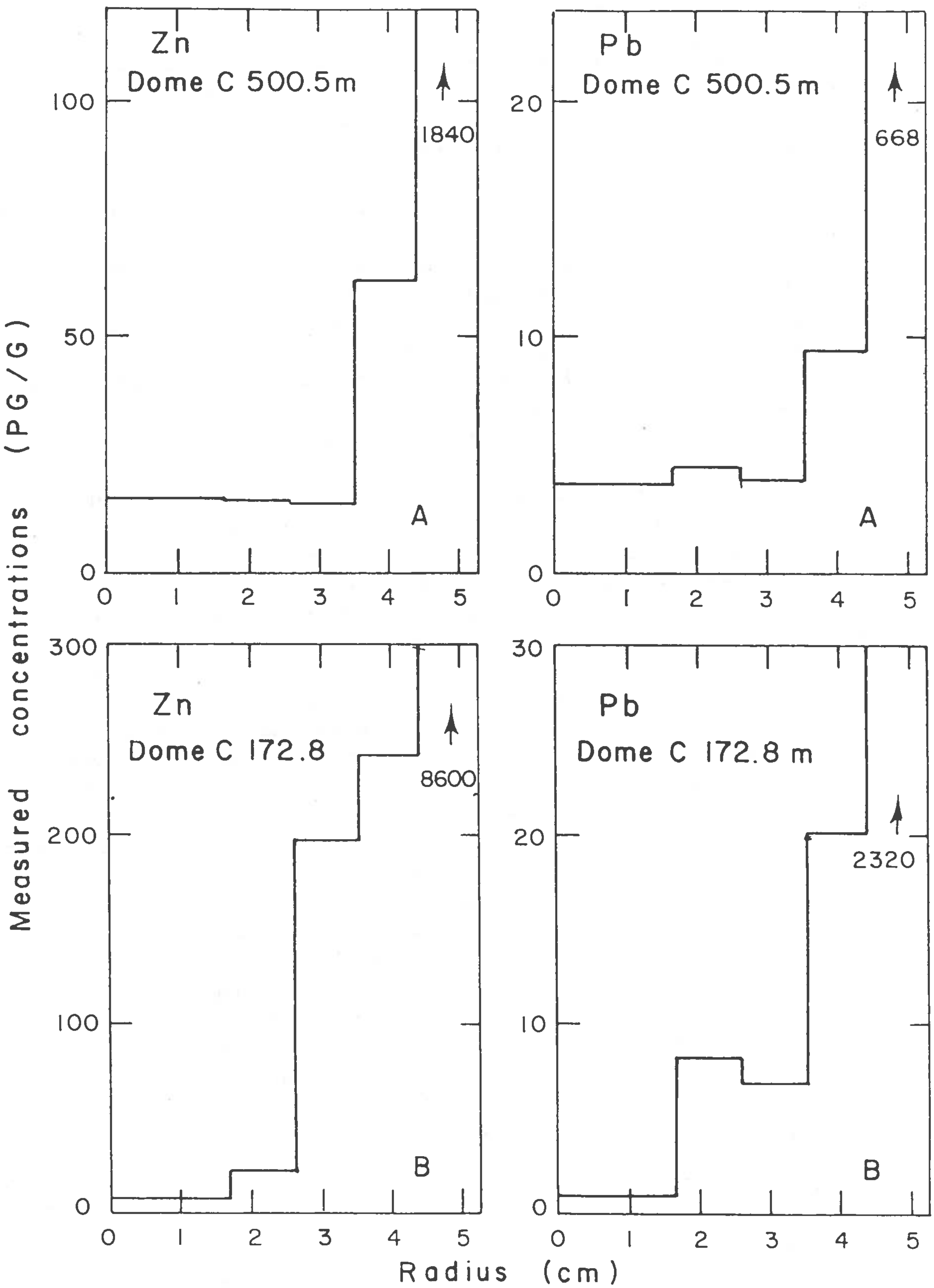

Figure 3 - Variations of Zn and Pb concentrations from the outside to the inside of two Dome C core sections as a function of radius. a) Dome C 500.5 m. b) Dome C 172.8 m.

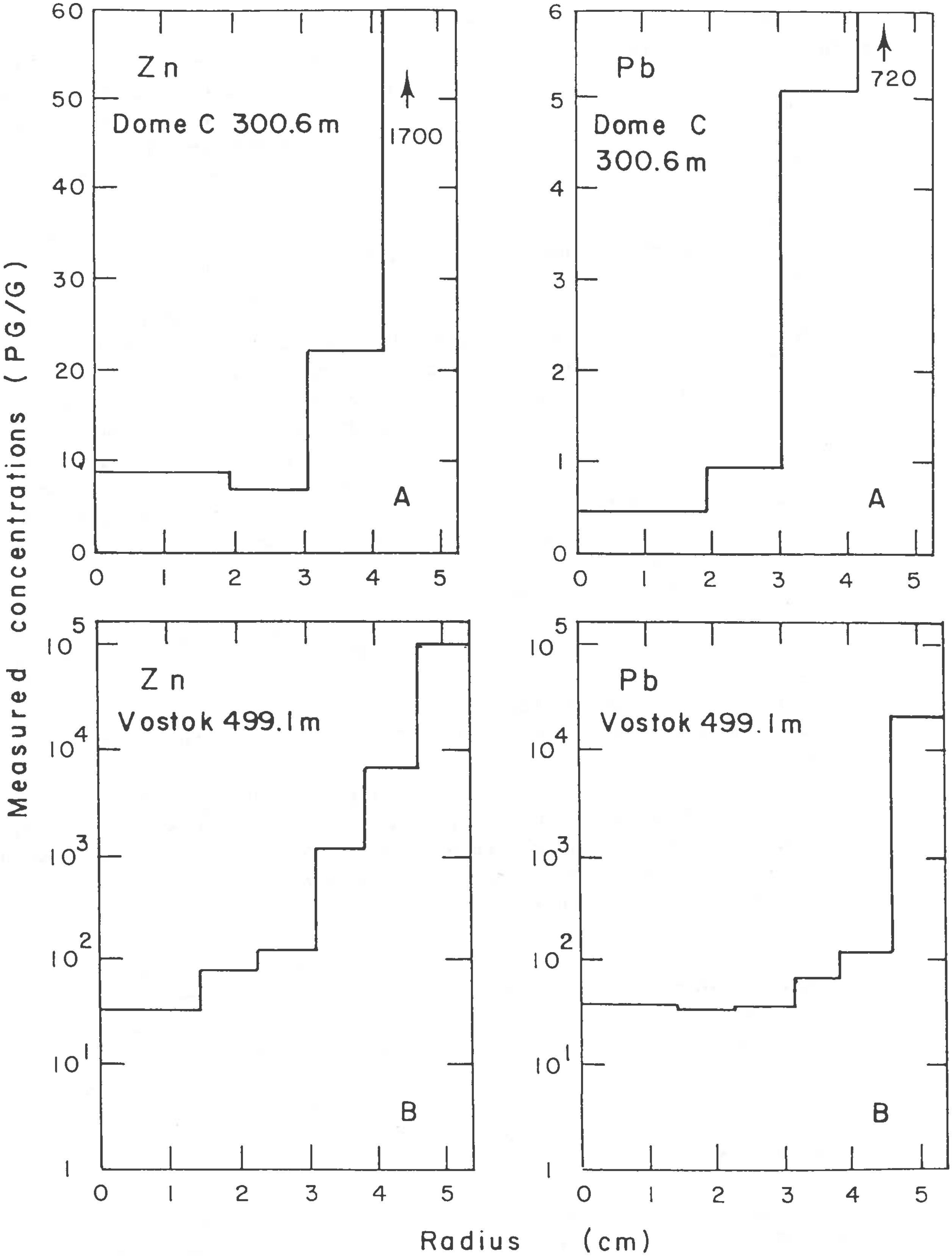

Figure 4 - Variations of Zn and Pb concentrations from the outside to the inside of one Dome C core section and one Vostok core section. a) Dome C 300.6 m. b) Vostok 499.1 m.

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A group of participants during the visit of the Argentiere Glacier.

LIST OF REGISTRANTS

AUGUSTIN L.
Laboratoire de Glaciologie et Géophysique de l'Environnement
B.P. 96, 38402 St-Martin d'Hères cédex, France

BAESSLER K.H.
Alfred-Wegener Institute for Polar and Marine Research, Columbusstr., D-2850 Bremerhaven, Germany

BARKOV N.I.
Arctic and Antarctic Research Inst., Beringua Street 38, 199226 Leningrad, U.S.S.R.

BOUTRON C.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

BURKHALTER J.
Physikal. Inst. Universitat Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

DELMAS R.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

DONNOU D.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

GERLI C.
Tecnospazia S.P.A., via Mercantesse 3, 20021 Baranzate di Bollate, Milano, Italy

GIRARD C.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

GUNDESTRUP N.S.
Geophysical Isotope Lab., University of Copenhagen, Haraldsgate 6, DK-2200 Copenhagen, Denmark

HAMMER C.
Geophysical Isotope Lab., University of Copenhagen, Haraldsgade 6, DK-2200 Copenhagen, Denmark

HANCOCK W.
P.I.C.O., 940 North 17th Street, Lincoln, NE 68588, U.S.A.

HANSEN S.B.
Geophysical Inst., Haraldsgate 6, DK-2200 Copenhagen, Denmark

IKEN A.
Versuchanstalt fur Wasserbau, Hydrologie und Glaziologie, ETH-Zentrum, 8092-Zurich, Switzerland

ISACKSSON E.
Dept of Physical Geography, University of Stockholm, 10691 Stockholm, Sweden

JOHNSEN S.J.
Science Institute, University of Iceland Raunvisindastofnun Haskolans, Dunhaga 3, 107 Reykjavik, Iceland

KELTY J.R.
3430 N 75th Street, Lincoln, NE 68588-0111, U.S.A.

KOCI B.R.
P.I.C.O., University of Nebraska-Lincoln, Lincoln, Nebraska 68588, U.S.A.

KUIVINEN K.C.
P.I.C.O., University of Nebraska-Lincoln, Lincoln, Nebraska 68588, U.S.A.

LEFEBVRE E.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

LORIUS C.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

MAGRIS E.
Tecnomare S.P.A., Societa per lo sviluppo delle technologie marine, 30124-Milano, Italy

MAITRE M.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

MANOUVRIER L.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

MAREC G.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

NIJAMPURKAR V.
Physical Research Lab., Navrangpura, Ahmedabad 380 009, India

OLESEN O.B.
Geological Survey of Greenland, Oster Voldegade 10, 1350 Copenhagen, Denmark

PEEL D.A.
British Antarctic Survey, High Cross Madingley Road, Cambridge CB3 OET, England

PERRIN J.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

PINGLOT F.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

RADO C.
L.G.G.E., B.P. 96, 38402 St-Martin d'Hères cédex, France

RUFLI H.
Physikalisches Inst., Universitat Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

SCHWANDER J.
Physikalisches Inst., Universitat Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

SEPPALA M.
Dept of Geography, Helsinki University, Hallituska, 11-13, SF-00100 Helsinki 10, Finland

SIMOES J.
Scott Polar Research Institute, Lensfield Road, Cambridge CB2 1ER, England

SONDERUP J.
P.I.C.O., 940 North 17th Street, Lincoln, NE 68588-0640, U.S.A.

STAUFFER B.
Physikalisches Inst. Universitat Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

SUZUKI Y.
Inst. of Low Temperature Science, Hokkaido University, Sapporo 060, Japan

ZAGORODNOV V.
Institute of Geography, USSR Academy of Sciences, Staromonetny 29, Moscow 109017, U.S.S.R.

CONTENTS

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