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ICE CORING AND DRILLING TECHNOLOGIES DEVELOPED BY THE POLAR ICE CORING OFFICE

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Abstract: The search for "zero defects" ice cores continues to challenge the ice coring and drilling community. No single drilling and coring device will fill all needs. Each project will have special requirements and will require an initial decision as to the most effective drilling system to be used as well as ensuring personal and environmental safety.

PICO has developed several types of drilling and coring systems from a lightweight hand auger to more complicated electromechanical drills (dry and fluid-filled holes) with rock-penetrating capability and thermal drills. Logistics considerations are important, and a comparison is made between the drill types associated with system weight, expected power and drilling liquid requirements, and fuel consumption.

Recent technological developments involve hot-water mechanical drilling, improvements in antifreeze and thermal drilling, the development of directional drilling, antifreeze dissolution drilling, and vibratory drilling.

1. Introduction

The Polar Ice Coring Office (PICO) was established by the U.S. National Science Foundation (NSF) in 1979 to continue providing drilling services for the scientific community at the end of the Ross Ice Shelf Project (RISP) in Antarctica. At the beginning of the 1980s, a core drilling inventory and capability was minimal. Because of this, attention was diverted to building drill systems that increased depth capability while reducing the logistics burden. The wide range of ice temperatures from 0°C to –57°C, physical characteristics of the ice, and depth requirements led to the development of a suite of drills that made it possible to obtain ice cores under a wide variety of natural conditions.

Numerous ice-core drilling systems have been developed and used over the past 30 years (Ice Core Drilling, 1976, 1989; Ice Drilling Technology, 1984). These systems produce core by cutting, shaving, or melting the ice. Physical designs of the many varieties of coring devices vary considerably. Each project has unique requirements and requires an initial decision as to the most effective drilling system to be used. Figure 1 schematically illustrates a decision tree for choice of a drilling system (RINALDI *et al.*, 1990). The two systems can be subdivided into various categories. Figure 2 illustrates several types of drilling systems from a lightweight hand auger to the more complicated electromechanical deep ice-coring system for use in fluid-filled holes. Table 1 further describes the capabilities of each type of drilling system, its use, depth capability, and core size. Approximate weight, power requirements, and fuel consumption are given to illustrate the expected logistic requirements associated with each ice-coring system.

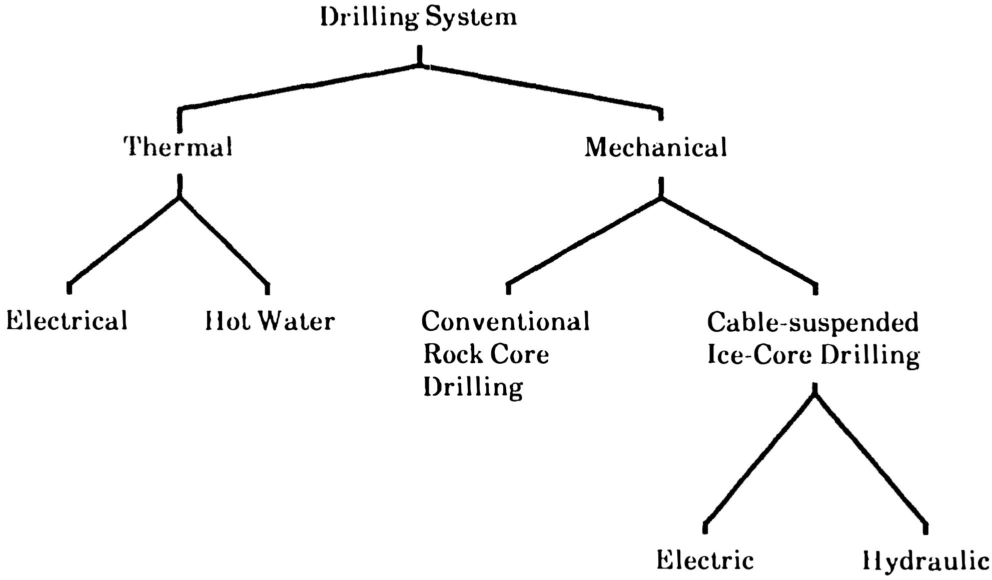


Fig. 1. Drilling system categories.

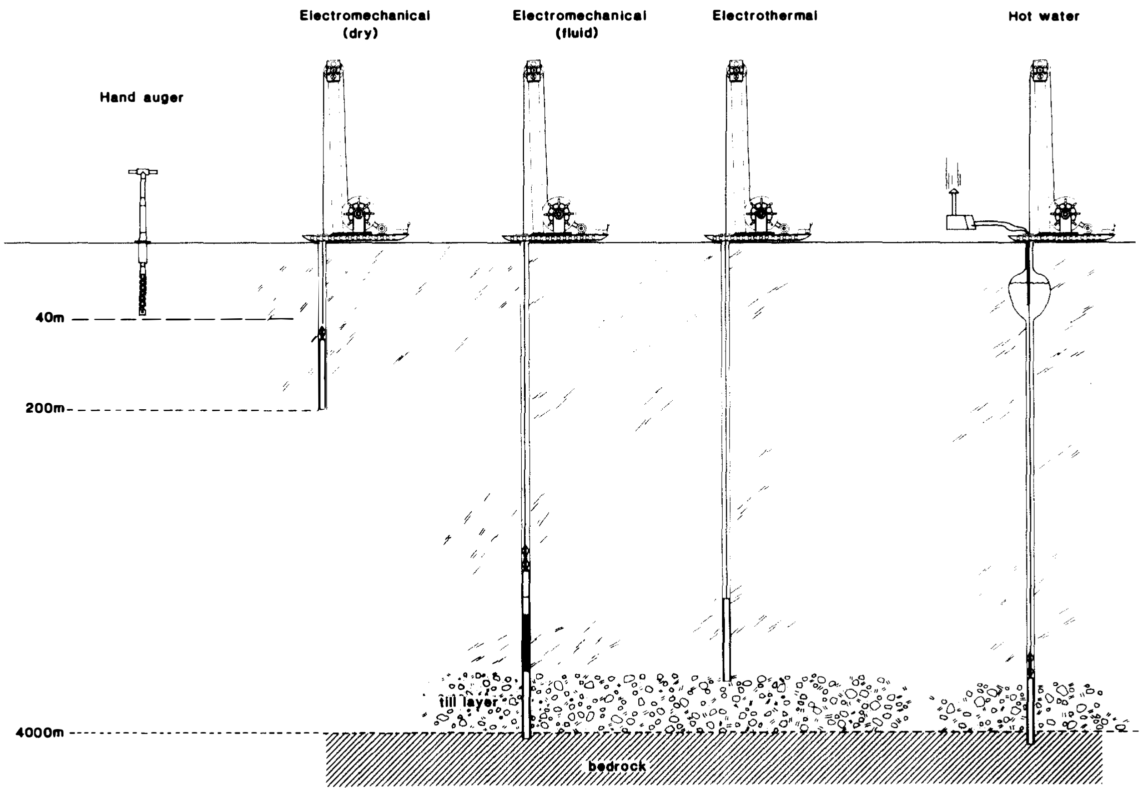


Fig. 2. Illustration of various PICO drilling systems and their capabilities.

Composite materials

Since many field investigations require operations on glaciers in remote regions of the world, lightweight, state-of-the-art materials are used to enhance design flexibility and minimize weight (Koci, 1989b). Figure 3 compares specific strength (strength/specific

Table 1. Description of PICO drilling systems showing capabilities, core size, weight, and power requirements.

Drill type	Depth capability	Use	Core size length	System wt	Power requirement	Expected fuel consumption
Hand auger	40 + m	Shallow sampling from a remote area	7.5, 10, 15 cm 1 m	100 kg 50 m system	--	--
Electromechanical (dry)	150 m below firn ice transition or 300 m	Deeper drilling (ice); remote area	7.5, 10, 13 cm 1 m	1000 kg with spares including generator	4 kW	200 L/200 m
Electrothermal	Depth of ice with fluid	warm ice, remote area	8 cm 3 m	20 kg (drill only)	4 kW	300 L/200 m
Electromechanical (fluid)	Unlimited including limited bedrock sampling	Sampling into bedrock requires major support and 25L or fluid per m	13 cm 6 m	5000 kg without generator or fluid	35 kW	15 L/hr
Thermal (hot water)	Unlimited; bedrock sampling (experiments)	Access to or sampling of bedrock. Size of system is a function of depth requirement	30 cm 10 + m	From 1000 to 10000 kg	40 kW	80 L/hr

gravity) to specific modulus (modulus of elasticity/specific gravity) for several composite materials, aluminum, and steel. The data show that the composite materials are stronger and stiffer than aluminum or steel on a per-weight basis.

Composites and composite fibers are incorporated in most PICO drills from the lightweight hand auger to the deep ice-coring drill. High strength-to-weight ratios and high tolerance to damage are among the reasons for the selection of composite materials. Kevlar, rather than steel, is used in drill system cables, which allows for weight reduction by a factor of eight-fold.

2. Ice-Coring Drills

2.1. Lightweight auger

Extensive use of glass epoxy composites has resulted in an auger capable of drilling in ice without the use of a tripod (KOCI, 1984; KOCI, 1989c; KOCI and KUIVINEN, 1984) to depths of approximately 30 m, or to 50 m with a tripod to assist in raising the drill string. The core barrel, available in either 1- or 2-m lengths, is a piece of 7.5-cm diameter (10- or 15-cm core size also available) composite pipe wrapped with two ultrahigh molecular weight polyethylene spirals riveted to the barrel. An aluminum adapter held in place by quick-release pins is used to connect the core barrel to the extensions. The extensions are

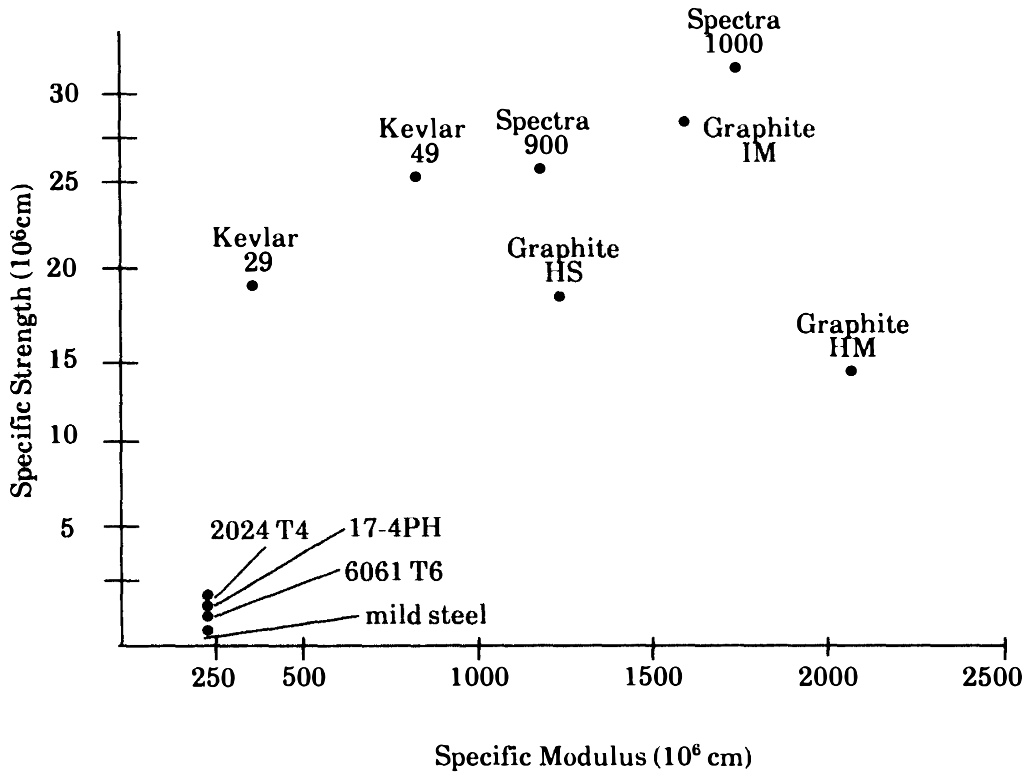


Fig. 3. Description of specific strength to specific modulus for various materials (Source: Addax, Inc., Lincoln, Nebraska).

5-cm-diameter composite pipes cut to either 1- or 2-m lengths with a weight of about 1 and 1.5 kg per meter extension, respectively. New extensions weighing 400 g/m are being fabricated from graphite and SPECTRA (Allied Fibers, Inc.). Extensions are screwed together. The strength of the joints and pipe used in the lightweight auger are more than adequate for all shallow drilling operations. Another advantage of using screw threads is that nothing protrudes beyond the outside diameter (O.D.) of the extensions, thereby eliminating the possibility of chips being scraped off the hole wall.

Cutting heads incorporate a tapered annulus and core dogs to insure positive catching of the core after each run down the hole. Adjustment screws are used to control the rate of penetration and to avoid jamming the drill head in the hole. The use of solar power and a small electric drive can be used to increase drilling rates. Solar power has been used to drive an electric motor (Koci and Kuivinen, 1984). Because only 250 W are required to drive the drill, the motor/power system is neither large nor heavy.

2.2. Electromechanical drill

The 10-cm core diameter electromechanical drill system (Fig. 4) is capable of drilling to 300 m and serves as an intermediate drilling system between shallow depths and deep ice coring well below the firn to ice transition. The system shown in Fig. 4 was transported to the Dunde Ice Cap, China (5400-m elevation), to drill three cores to bedrock, each yielding approximately 135 m of core.

A 308-m core was obtained during the summer of 1993 from the Guliya Ice Cap

(6200 m), China. Retrieval of ice core from over 200 m below the firn/ice transition required a change of drill type from electromechanical to thermal (KOCI and ZAGORODNOV, 1994).

2.3. Thermal systems

Thermal-electric drilling systems use drilling heads in which heating elements are circularly embedded (Fig. 5). When the heated head is lowered into the ice, it melts a circular ring and penetrates deeper into the ice. The ice core then moves deeper into the chamber of the drilling system (RINALDI *et al*., 1990).

The PICO electrothermal drill consists of a heating element attached to the end of a core barrel. The heating element is unique because it is hermetically sealed and pressure tight to approximately 500 psi. It can provide power in excess of 40 W/cm^2. Heat-transfer efficiency is high because the heating elements are in direct contact with the ice. Maximum power dissipation is 8.000 W in a 10-cm diameter, 0.63-cm-thick ring. If the ice is colder, the ice core tends to fracture. This type of thermal drill is useful for shallow and intermediate depths (KOCI, 1985).

In 1983, a lightweight winch with Kevlar cable was developed for use in high-altitude, remote areas of Peru. The thermal drill described above was used to collect cores to bedrock on the Quelccaya Ice Cap (14 S, 70 W). A 2-kW array of solar voltaic panels was used to provide power. An electromechanical drill was used to make two starting holes through the firn to a depth of 35 m. Thereafter, a thermal drill was used to collect core to bedrock, which was reached at 163 m and 154 m (KOCI, 1985). A similar system with an electromechanical drill was used to drill three holes to bedrock (135 m) on the Dunde Ice Cap, China.

All PICO drills can use a variety of power sources. A 2-kW array of Solarex, Inc., HE-60 panels (Fig. 6) was used on the Quelccaya Ice Cap in 1983 to power the electromechanical and thermal drills.

Thermal electric drilling is slow and power-consuming. The presence of water in the hole can result in freezing in the drill system. There is also concern about fracturing the core. Thermal drills have limited capabilities in penetrating dirty ice.

Hot-water drills are used extensively to provide access holes for instrumentation and seismic investigations. The drill system consists of a downhole hose and nozzles, winch, mixing manifold, and sled-mounted standard car wash heaters to provide hot water (Fig. 7). During the 1987-88 field season, two holes were drilled (370 m and 480 m) through the Crary Ice Rise, Antarctica (83 S, 170 W), to install thermistor cables (KELLEY and KOCI, 1990). The hot-water drill melted a hole 25 cm in diameter at an average drilling rate of 0.5 m per minute. Instrumentation on the drill stem included inclinometers to measure the tilt of the hole, thermistors to measure the water temperature and heat loss, and calipers to measure the size of the hole. Based on modeling, hot-water drilling techniques are capable of reaching depths greater than 2000 m (DAS *et al*., 1992).

2.4. Deep ice-coring system

Core quality rather than hole closure limits maximum drilling depth in a dry hole. Addition of a fluid not only compensates for the overburden pressure, but aids the drilling process by enhancing chip removal and damping vibration in the drill. Beyond that depth,

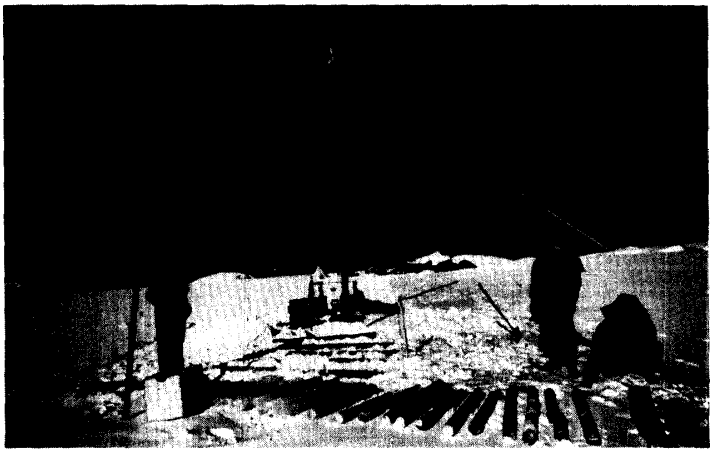


Fig. 4. 200-m electromechanical ice coring system. Dunde Ice Cap, China. 10-cm ice cores are in the foreground.

Fig. 5. PICO electrothermal drill capable of taking an 8-cm diameter ice core.

Fig. 6. 2 kW solar-powered drill system. Quelccaya Ice Cap, Peru, 1983.

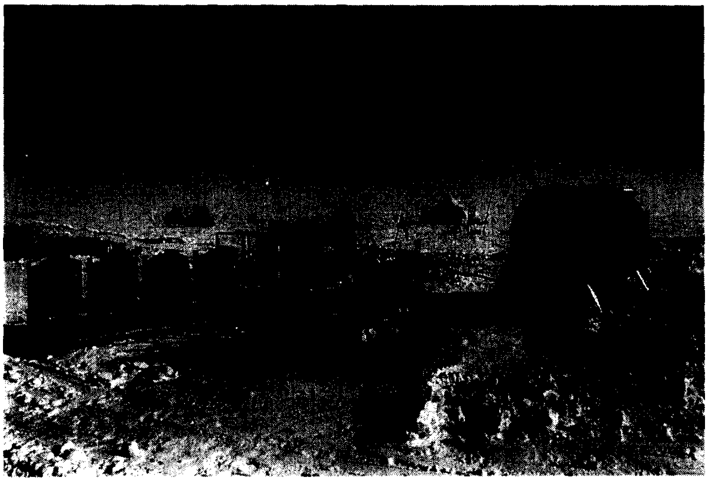


Fig. 7. PICO hot-water drill. A modular approach is used in construction.

the ice becomes brittle due primarily to high bubble pressure in the ice. The practical limit to open-hole drilling is in the 200- to 300-m range (KOCI, 1989a).

A major drill development initiative was undertaken in 1988 to design and build a drill capable of extracting high- quality core through the Greenland Ice Cap (3200 m). Development of this 13-cm drill was an expansion of the standard 4-inch PICO dry-hole drill. The deep-drill design was based on the incorporation of a pumping and filtering mechanism for operation in a fluid-filled (butyl acetate) hole (GOSINK *et al.*, 1991).

Figure 8 is a schematic diagram of the deep ice-coring drill that was used to acquire ice cores through the Greenland Ice Cap to a depth of 3053 m in support of the GISP-2 project, Greenland Ice Sheet Program.

The drill consists of a cutting head with core dogs, core barrel, pump section, well screens, D.C. motor with gear reducer, instrumentation and switching section, transformer, anti-torque, and slip rings. Overall, the drill string is approximately 22- to 29-m long (PROENZA *et al.*, 1990; RINALDI *et al.*, 1990).

As the drill bit cuts the ice, chips and fluid are pumped into the filter, where chips are removed and the fluid allowed to recirculate. An instrument section (HANCOCK and KOCI, 1989; HANCOCK, 1994) monitors depth, inclination in two axes, azimuth, motor current, fluid pressure and temperature in the hole, cable tension, and other variables as needed. The drill is suspended by Kevlar cable with wires embedded and powered from the surface.

PICO searched for an appropriate drilling fluid that would be environmentally safe and meet as closely as possible specific drilling fluid requirements (Table 2). Of nearly 250,000 compounds surveyed electronically, 11 potentially suitable fluids were found. Of these 11, only two, butyl acetate and anisole, fully met the constraints imposed by technical, scientific, health, and safety concerns (GOSINK, 1989). The butyl acetate is satisfactory for most of the above requirements. The density of butyl acetate was found to increase with decreasing temperature. Because the minimum internal temperature in the upper kilometer of the Greenland ice sheet has been observed to be −31°C, and minimum temperatures are expected to be colder in Antarctica, an added densifier is required.

A study of ethanol as a drilling fluid with respect to its effect on ice has recently been concluded (GOSINK *et al.*, 1991). Aqueous ethanol may also be a useful ice core drilling

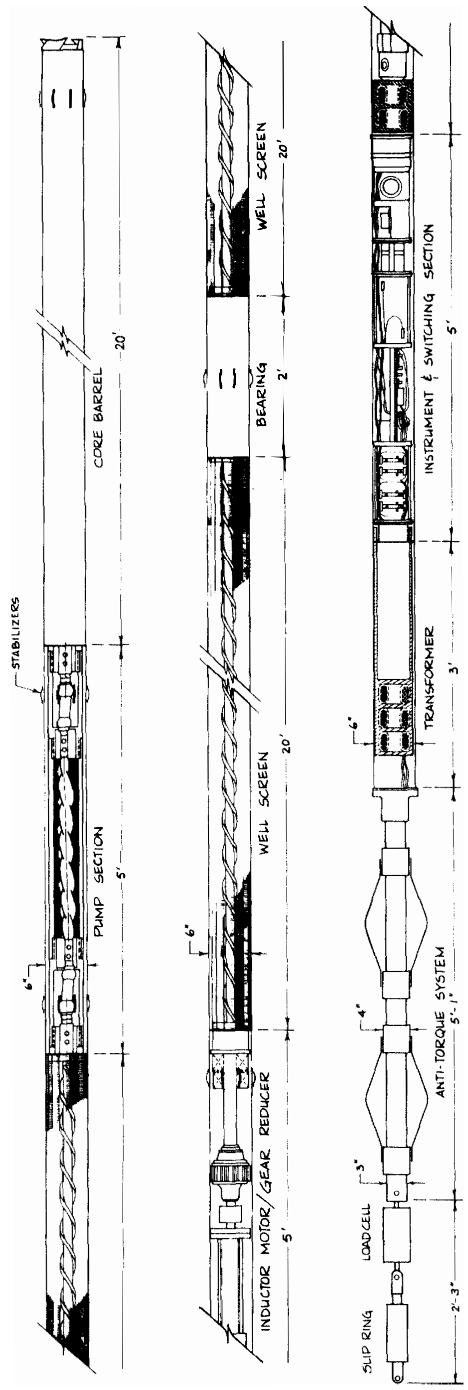


Fig. 8. Schematic of PICO deep ice coring drill.

fluid where the purpose is to obtain high-quality cores for glaciochemical analyses. It has been used successfully in thermal drilling (ZAGORODNOV *et al.*, 1992).

PICO has also modified its deep-coring drill to accept a rock-drilling bit to penetrate the rock substrate under the ice (Fig. 9). A 155-cm length of rock core (3.34-cm diameter) was recovered. The ice was frozen to the bedrock.

Table 2. Specific drilling fluid requirements for PICO drills.

1. Non-toxic
2. Chemically clean
   a. no salt ions
   b. Not to interfere with analysis for:
      i. Al, Pb, Zn, Cu, Cd, Se, As, Sb
      ii. oxygen isotope rations
      iii. CO_2 and C^{14}
3. Hydrophobic (will not attack ice)
4. Viscosity (less than 5 cp)
5. Density 920 kg/m^3 at −50 to 0°C
6. Will not attack drill materials
7. Dielectric desirable

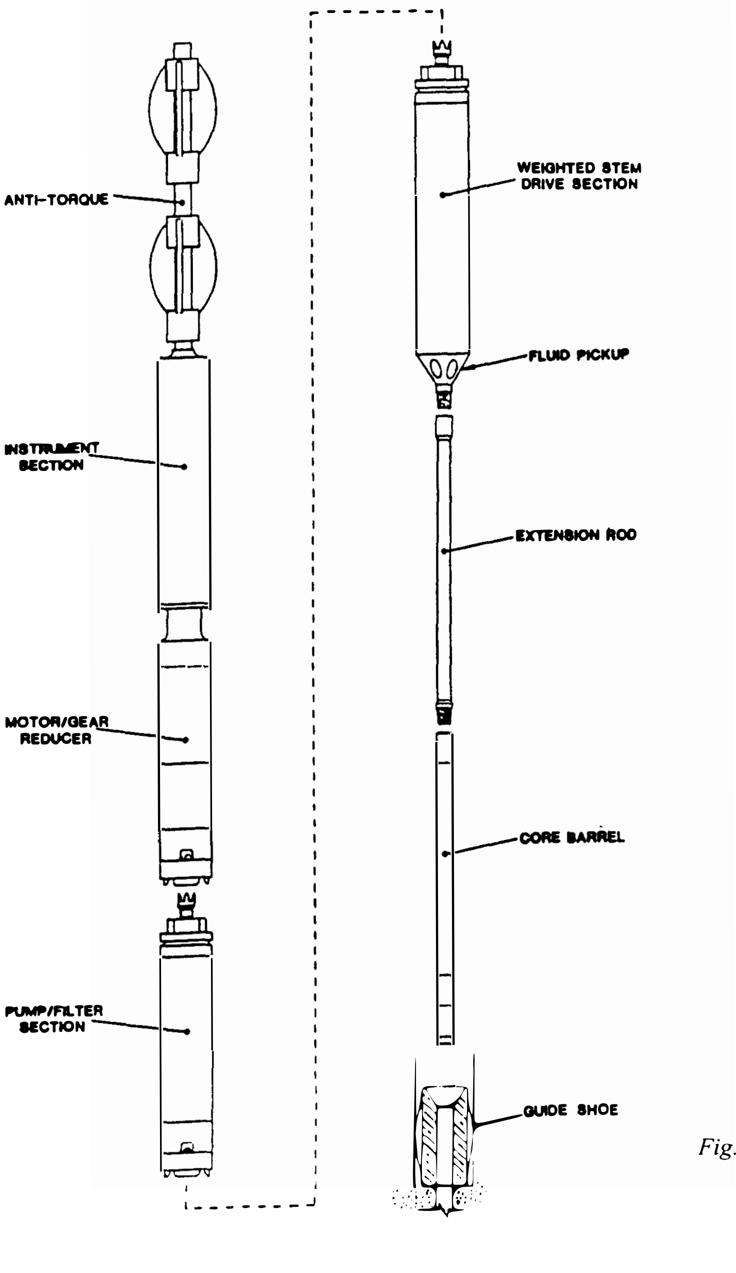


Fig. 9. Schematic of rock-coring drill adapted for use on the PICO deep ice coring drill.

2.5. Drill heads and cutters

Drill heads and cutters currently are machined on a 4- axis CNC milling machine. We are currently investigating the petroleum industry's use of matrix drill heads with replaceable steel or carbide cutters. An example of a drill head and cutter is shown in Fig. 10.

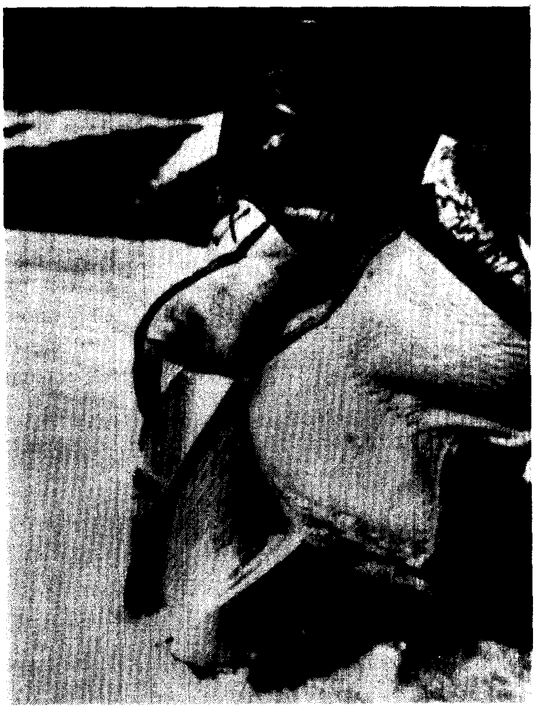


Fig. 10. 10-cm drill head and cutter used on PICO drill systems.

2.6. Deep-drill handling system

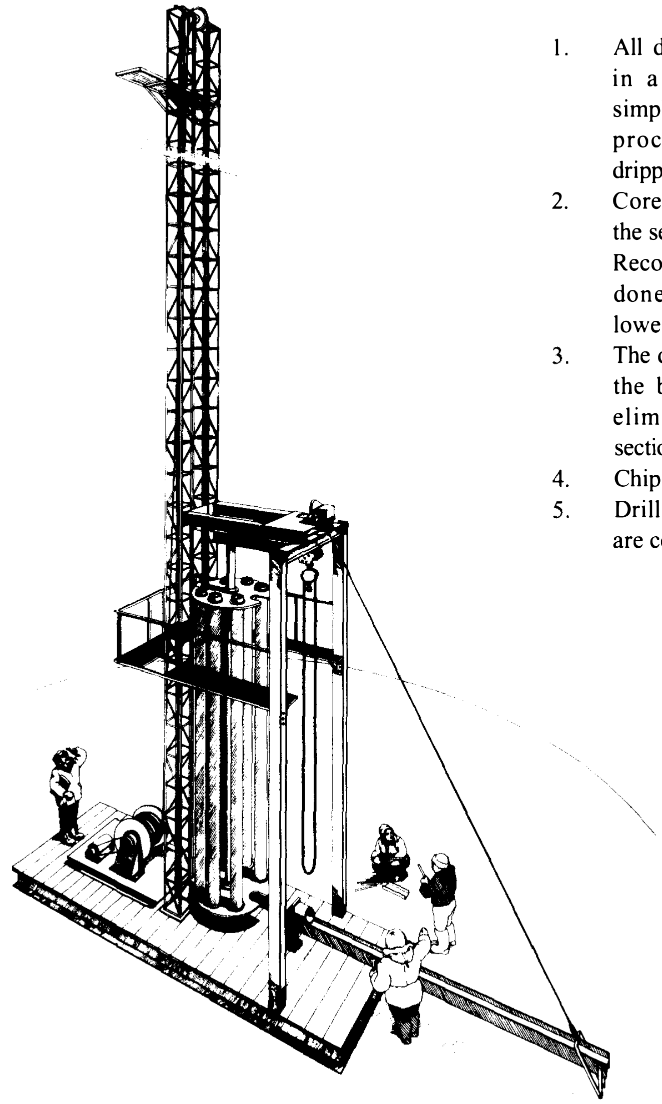
A carousel drill-handling system (Fig. 11) was designed and constructed to support the deep ice-coring drill in the Greenland Ice Cap during the GISP-2 Program. The carousel is used to break the 24-m drill string into 6-m sections.

Construction of the drill-handling system (WUMKES, 1994a, b) utilizes aluminum and composite materials. Drill components are stored in fiberglass-epoxy (AMERON) pipe. These pipes also contain the butyl acetate wash system (GOSINK *et al.*, 1991) used in the removal of chips from the well screen sections in the drill. The chip/slurry mixture is collected in a drain pan located under the carousel. An auger removes the chips to a holding tank where the butyl acetate drilling fluid is removed by a centrifuge and recovered.

Handling of drill-core barrels is accomplished by use of a tilt-table made of an aluminum beam. The only drill component that is laid down is the core barrel. Once the core barrel is in a horizontal position, the head can be serviced and the core removed. The core is logged and cut into 2-m sections, then placed in a polyethylene tube in 2-m core trays.

2.7. Cable for deep drilling in fluid holes

The use of Kevlar as a strength member in ice-drilling cables began in 1983 with the



1. All drill components are handled in a vertical position. This simplifies the disconnect/connect procedure and minimizes dripping of the drill fluid.
2. Core removal is efficient, as is the servicing of drill components. Reconfiguring of the drill can be done while the drill is being lowered down the hole.
3. The drill is never dismantled over the bore hole. This procedure eliminates the possibility of a section free-falling to the bottom.
4. Chip removal is simplified.
5. Drilling fluid and soaked chips are contained closely.

Fig. 11. Deep ice core drill handling system.

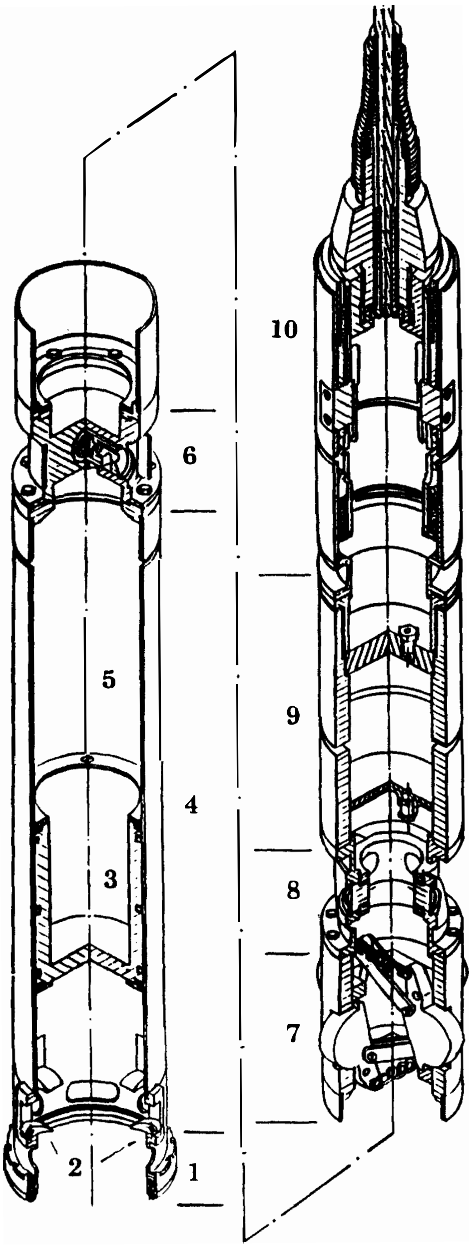
Quelccaya Expedition. The 7:1 strength to weight advantage over steel reinforced cables was the single advance that made that project possible. Successful use over a period of eight years suggested that the use of Kevlar cable in a deep-drilling project would keep downhole weight to a minimum while providing enough power to run a drill capable of drilling into bedrock. The Kevlar cable weighs 400 kg in the drill fluid at 3000 m while a steel cable weighs 3500 kg.

Borehole fluids eventually remove the cable lubrication which degrades the cable fibers during the many trips of the cable over a sheave. More conservative operating standards must be used.

At the beginning of the GISP-2 project, cable specifications were 10 times expected tension. Chafing of the cable strength members resulted in significant strength loss during the 1992 season which halted drilling early. Subsequent investigations have shown that similar results have been observed in cables immersed in sea water working near the suggested limits. In the case of GISP-2, increase in drill weight and normal winching procedures produced loads exceeding the 10:1 safety factor while sheave diameter remained at 30:1. Spooling problems and cable jumping may have also contributed to the problem. It is suggested that when using butyl acetate as a borehole liquid, the cable strength should be at least 10 times or more the anticipated load, and sheave diameter should be 40:1. New fibers or new lubricant impregnations may also be useful.

2.8. Development of alternative drilling systems

Currently, PICO is investigating alternative systems to produce high-quality ice cores and to minimize cost, weight, and size of the equipment. Two prototype drills are under



Drill Description

1 - drilling head
2 - core catchers
3 - piston
4 - core barrel
5 - antifreeze
6 - fluid filling inlet
7 - universal coupling
8 - antitorque
9 - instrumentation package
10 - suspension, cable termination

Antifreeze Thermal Electric Drill Specifications

Temperature of ice	- 0 to –60°C
Heater outer diameter	- 114 mm
Heater inner diameter	- 102 mm
Borehole diameter	- 130-136 mm
Drill length	- 4.5 m
Core length	- 3 m
Drill weight	- 60 kg
Power consumption	- 3 kW
Drilling rate	- 5 m/h
Penetration rate (2 shift depth 3000 m)	- 420-650 m/week

Fig. 12. Antifreeze Thermal Electrical Drill (ATED).

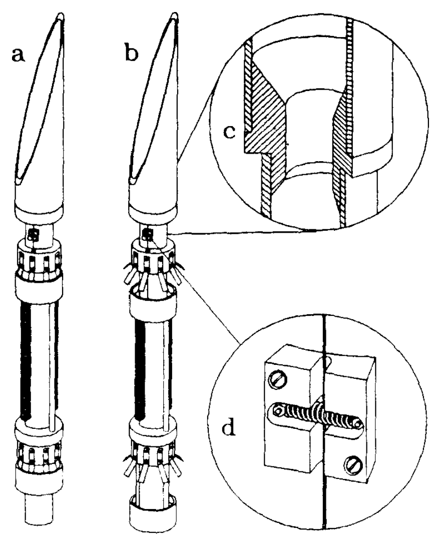
consideration: a hot-water mechanical drill (KELLEY and KOCI, 1990; DAS *et al.*, 1992) and a new version of an antifreeze thermoelectric drill (ZAGORODNOV *et al.*, 1992, 1994a). Figure 12 describes the prototype thermal dissolution drill. Laboratory experiments show that this drill can offer low thermal effect on an ice core and ice wall. It also shows promise to penetrate "dirty" ice and has low power consumption and low logistical support cost.

The principle of operation of the antifreeze thermal electrical drill (ATED) is that the drill is immersed in an antifreeze solution, *e.g.*, ethanol/water, glycols, etc., in the borehole. The drill is fitted with a heating element that melts the ice. The melt water mixes with the antifreeze solution. The concentration of the antifreeze maintains the freezing point equal to the temperature of the surrounding ice.

The new design ATED offers simple mechanical structure that may offer greater decrease in thermal shock to the ice core than previous ATEDs, as well as increased travel speed in high-viscosity solutions. Numerical modeling based on experimental data shows that the magnitude of thermal elastic stresses in the ice core due to the drilling-melting process can be reduced from 5 to 6 times (NAGORNOV *et al.*, 1994). This should allow for high-quality ice cores to be obtained from glaciers that are at –60°C.

Penetration rates are expected to increase over older models. The ATED can also be used for directional drilling. Drilling costs may be substantially reduced for deep and intermediate drilling, compared to other methods.

A recently designed device called a whipstock (Fig. 13) was used to deflect an ATED in a previously drilled borehole (ZAGORODNOV *et al.*, 1994b). The test demonstrated that a whipstock deployed in the main borehole permits directional drilling to obtain extra ice cores. The whipstock was placed 25 cm above the bottom of a 4.5-m deep borehole. The



Whipstock : a - Lowering (initial) stage,
b - working stage,
c - neck,
d - heating releas mechanism.

Fig. 13. Whipstock used for the directional drilling.

ATED was inclined in the previously prepared cavity to an angle of up to 3°. When the second borehole reached a depth of about 6 m from the whipstock, it had no inclination. The distance between axes of the main and secondary boreholes was about 0.3 m. The whipstock was frozen into the main borehole during directional drilling, and afterwards, it was heated electrically and removed from the hole.

Results of the test of the whipstock showed:

1) The whipstock prototype is practical for antifreeze thermo-electric ice coring. No extra surface equipment is needed for directional drilling.
2) Only eight extra hours were needed for placement (about 4 hours) and recovery (about 4 hours) of the whipstock in the borehole.
3) The secondary borehole regains its vertical trajectory about 6 m down from the whipstock.
4) The whipstock can be recovered, even when the borehole freezes or is deformed by shear.
5) The angle of deflection of the secondary shaft depends on cavity diameter, not the slope angle of the upper surface of the whipstock. The maximum angle of directional drilling (DD) with the antifreeze thermal drill is estimated to be 40° to 50°.
6) The access hole in the center of the whipstock allows scientific equipment to be lowered for simultaneous use in one or more secondary boreholes.
7) Borehole logging equipment can be deployed with the whipstock placement device to permit DD in specific azimuth direction.
8) Special heaters can be deployed to melt the cavities in 0.5 to 1 hr.
9) The whipstock can be deployed with a rubber packer, which permits use of the ATED in boreholes filled with hydrophobic liquids (DFA, kerosene, butyl acetate).
10) Combined deployment of an electric thermal drill, a whipstock, and placement of logging equipment will make the following possible:
    - Additional ice cores from any depth and azimuth; and
    - "Fresh" ice cores from "old" boreholes: Camp Century (1966); Byrd Station (1968); Dye-3 (1981); GISP; GRIP

Directional drilling technology can provide additional boreholes and ice core from any desired depth at any time.

Recently, the Antarctic Muon and Nutrino Detector Array (AMANDA) Program was initiated at South Pole Station, Antarctica which requires placing strings of 20 photomultiplier tubes 30 cm in diameter to depth of 1100 m. Drilling is currently carried out by hot-water techniques. Drilling a large-diameter hole in ice that is –50°C to the bottom requires 1 MW of heat, which places a large logistics burden on the South Pole Station. PICO is investigating the use of solar concentrators, which can ease or eliminate this burden and provide electricity for the station during the summer months.

An expansion of this drill type into coring operations is possible for basal ice and subice sampling. The use of water as a drilling fluid is environmentally clean, and by using it as a hydraulic fluid with downhole mud motors or vibrators, many new areas of coring beneath the ice become available.

The study of snow-firn sequences of glaciers by pit excavations takes a considerable amount of time. Rapid penetration of snow-firn layers can be accomplished by using a large-diameter vibratory drill.

The vibratory drill (Fig. 14) includes a core barrel with a hardened steel tip and a 1.5 kW electrical motor- vibrator. The vibrator provides vertical vibration to the core barrel with 50 Hz frequency. The penetration of the drill into the glacier occurs as the tip displaces snow or firn. Displacement of some of the material by the tip causes a compacted layer on the surface of the core which increases friction on the inside of the core barrel causing the core to stay inside the barrel. The vibration helps the core stick in the tube and makes the extraction process easier. An electric winch and cable are used to raise and lower the drill in and out of the borehole.

Field tests show a drill penetration rate of 6 to 8 m/min in a snow-firn layer at –50°C. One complete drilling cycle requires 1 to 5 minutes and includes:

- lowering the drill,
- penetrating the core barrel into the firn,
- breaking the core, and
- extracting the core.

The depth of the borehole is increased 1.2 m with each drilling cycle. Although the vibrator should be operated during core breaks and extraction of the core from the borehole, it does cause destruction of one-third of the top and the bottom of the core.

A winch capable of producing a line tensile force of 3000 N with a variable line speed for both penetration and hoisting is necessary to avoid destruction of top and bottom

Drill Description

1 - hand steel tip
2 - core barrel
3 - shock absorber
4 - electrical motor-vibrator
5 - armored cable

Vibratory Drill Specifications

Outer diameter	-	0.4 m
Snow or firn core diameter	-	0.38 m
Drill/Core length	-	2.2/1.2 m
Power consumption	-	1.5 kW
Vibrator frequency	-	50 Hz
Drilling rate	-	6-8 m/min
Penetration rate	-	12-20 m/h
Weight	-	80 kg

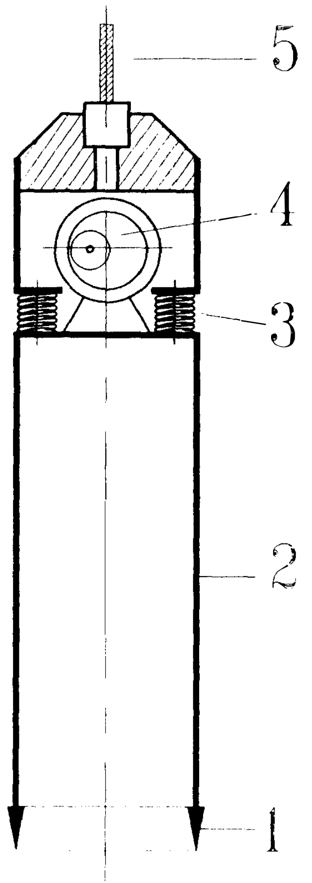


Fig. 14. Vibratory drill for drilling large-diameter boreholes in snow and firn.

sections of the core. Power requirements for 0.8- to 1.0-m diameter boreholes in snow and firn should require from 5 to 8 kW. Weight of the vibratory drill should be about 300 kg. The total weight of the equipment for large-diameter borehole drilling is estimated to be from 600 to 800 kg.

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