GISP2 DEEP ICE CORE DRILLING

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The Polar Ice Coring Office (PICO) was established by the U.S. National Science Foundation (NSF) in 1979 to provide coordinated drilling services for the scientific community. During the past five years PICO has been operated through the University of Alaska Fairbanks (UAF). Within that time, the Greenland Ice Sheet Project (GISP2) was successfully conducted. There were three major functions of PICO involvement in the project: (1) deep ice core drilling, (2) logistic support of field operation, and (3) management. To support these activities, PICO developed new ice and rock core drilling technologies, logistics systems, and lines of organization. The scientific success of the GISP2 project was directly associated with these technical and organizational developments.

History of the U.S. deep ice core drill

The first scientific approach to deep ice coring was proposed and accomplished for the glaciological program of the International Geophysical Year by the U.S. Army

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SIPRE. Between 1956 and 1958, four deep holes were cored by modified conventional rotary equipment. In the summers of 1956 and 1957 boreholes of 305 m and 411 m were drilled in northwest Greenland at Site II. In Antarctica at the beginning of 1958, a 308-m borehole was drilled at Byrd Station. By the end of the year, a 256-m borehole was drilled on the Ross Ice Shelf at Little America V. During that time, the major elements of ice drilling technology were successfully tested. Among these were a technique of borehole casing for use with a cold-air chip transport system, coring bits, and a constant-rate feed device. First successful drilling with a hydrophobic drilling liquid (Diesel Fuel Arctic grade or DFA) was completed in the Little America V borehole in the last 5.5 m. This section of ice core had only a few cracks, and they did not penetrate the ice core deeper than 12 mm. At that time the use of liquid in the borehole for obtaining good quality ice core was proposed and certain problems were recognized. The use of industrial-type drilling equipment had several drawbacks: heavy weight (3 shipments; 40 tons), long setup time, slow performance, and poor ice core quality (Lange, 1973).

In 1961 and 1962, dry and oil-filled boreholes were drilled at Camp Century in Greenland with cable-suspended thermal drills developed by U.S. Army CRREL specialists (Ueda and Garfield, 1969b). After field tests, it was found that these drilling systems were not reliable for a proposed 2000-3000-m-deep ice coring (Bader, 1962). The first cable-suspended electromechanical rotary drill suitable for glacier ice operations was developed at CRREL in 1964 (Ueda and Garfield, 1968). This drill was a modified rock drill developed by Armais Arutunoff. In 1968 and 1969, it was successfully used for deep drilling at Camp Century (Greenland) and Byrd Station (Antarctica), where holes of 1390 m and 2164 m were drilled. The average drilling rate was about 2.5 mm/s which is close to that of a conventional pipe-driven drill, but the core quality and penetration rate were significantly improved. The deep portion of the Byrd Station hole was filled with a DFA and trichlorethylene (TCE) mixture to maintain a proper density of the borehole liquid (920 kg/m^3). About 22 m^3 of ethylene glycol were used during the Byrd Station deep drilling, along with 49 m^3 of DFA and 8 m^3 of TCE.

In the 1970s, a last attempt to modify the rotary pipe-driven drilling system for use in cold ice drilling to depths greater then 1000 m was made (Hansen, 1976). From previous experience with rotary drilling on glaciers, it was clear that industrial-type drilling equipment is too heavy (Lange, 1973). Special fiberglass-reinforced epoxy pipes (FRP) with steel connectors were designed at CRREL. Compared with industrial-type drill pipes, FRPs are from 3 to 10 times lighter. To avoid the time-consuming hoisting and disassembly of the drill pipe, the core was retrieved by a wireline system: a core barrel coupled with cable. The core-loaded barrel travels inside the drilling tubes suspended by a cable. Therefore, the ice core can be retrieved without disassembling the drilling pipe string. Reduction of the drilling rig weight was made by using a reverse air-vacuum or reverse air circulation for removal of the cuttings. This makes it possible to exclude heavy air-cooling devices. Adaptation of the system for drilling on the East Antarctica Ice Sheet to a depth greater than 1000 m employed circulation of cold DFA. This system was used during the 1976-77 season for core drilling (air-vacuum) to a depth of 313 m (Antarctica, Ross Ice Shelf, J-9). During the 1977-78 season the wireline coring system was used with cold DFA circulation to remove cuttings from a 170-m borehole. For various reasons, the full potential of the drilling system was never realized. However, it appears that the system is ideal for drilling intermediate-depth (a few hundred meters) boreholes in regions with good surface transportation conditions. This system is also capable of coring subglacial material. Use of chilled drilling liquid (for environmental reasons, DFA is no longer acceptable) may provide freezing of unconsolidated subglacial deposits and permit coring.

The next advance in deep ice drilling technology happened at the end of the 1970s, when a new electromechanical drill (ISTUK) was built at the University of Copenhagen (Denmark) (Gundestrup et al., 1984). The ISTUK drill was developed as a part of the Greenland Ice Sheet Program (GISP) conducted by Denmark, Switzerland, and United States investigators (Langway et al., 1985). The major drilling principles remain the same as with the CRREL and other electromechanical drills, but several innovations for reduction of drill weight and power consumption were used. The direct result is a reduction of cable diameter and weight of the winch. To compensate for the lithostatic pressure of the ice, the hole is filled with a hydrophobic liquid. For reasons of higher purity, Jet A-1 (aircraft fuel) was used as a major component of the borehole liquid. To maintain the density of the liquid close to that of ice, perchlorethylene (PCE) was added to the kerosene. Addition of 10% of PCE was enough to increase liquid density to 950 kg/m^3. Compared with TCE, the PCE presents less inhalation danger due to a lower vapor pressure. However, to reduce the presence of the toxic fumes from the borehole liquid, a ventilation system was used in the drill shelter.

The ISTUK drill was successfully used for deep drilling in Central Greenland at the Dye 3 Station where a 2037-m hole was drilled during 1979-81 as part of the GISP project. Then during 1990-92, a 3029-m hole was drilled at Summit Greenland Ice Sheet (GRIP project). Excellent quality ice cores were obtained. The investigations in central Greenland show that the ISTUK drill cannot operate below -40°C, or much deeper than 3000 m, and is not capable of rock coring.

To have a reliable drill for coring in the central regions of Greenland and the Antarctic Ice Sheet at ice temperatures to -55°C and depths to 4000 m, a new development program was proposed (Recommendations for a U.S. Ice Coring Program, 1986).

PICO electromechanical ice core drill

The concept of the drill including a description of its main elements and operating principles was proposed by B. Koci in 1986 (Koci, 1988). In this development, the idea of a modular drill was suggested. As a result, the drill is capable of dry hole coring, deep fluid-filled-hole ice core drilling, and debris-laden ice and rock coring. The specification of this drill is shown in Table 1 (Kelley et al., 1994; Stanford, 1994; Wumkes, 1994).

The drill sections are connected in the following top-to-bottom sequences: slip ring, load cell, anti-torque system, transformer section, electronic instrument section, DC motor (0-2500 rpm), gear reducer (ratio 17:1), first filter section, bearing section, second filter section, pump, core barrel, and cutting head (0-150 rpm). The drilling head is rotated by a long shaft which passes through the filter sections and which also drives a Moyno type pump.

The coring head consists of three cutters and three core catchers similar to PICO shallow-depth drills. Two cutter profiles have been tested. The shallow chevron profile cutters were developed for stabilization of the drilling head and reduction of axial vibration. A more common type of cutters with a straight cutting edge shows essentially the same core production capability. However, the straight-type cutter produces a larger, more easily trapped ice chip. Both cutter types were used with a penetration shoe which controls the amount of ice removed with each revolution of the cutting head. Experiments with aggressive carbide edge cutters demonstrated excellent cutting ability, but their construction exhibited brittleness and fragility, particularly when any debris was encountered in the borehole

At first the drill was used for boring and reaming a dry hole. This was necessary for casing the upper portion of the deep borehole to prevent migration of the drilling fluid through the firn. Chips from the cutting head are transported to the collecting screen inside the inner core barrel (above the core) by helical flights similar to shallow dry-hole drills. Three vertical strips were welded inside of the outer core barrel to help provide circumferential shear for moving chips to the chip collector. For further fluid drilling, a double-tube core barrel without flights or strips has been used very successfully. In this case the ice chips and drilling liquid mixture are sucked up through the annulus between the inner and outer core barrel tubes and then pass through the Moyno pump and the filter. Though it is heavy, the Moyno pump has several advantages. It can pump fluids with a wide range of viscosities. It is robust and capable of pumping ice chips (with rock fragments) in the drilling fluid with minimal damage. It is powered by the same shaft that turns the core barrel and works well in the required rpm and power range.

The design of the cuttings filter was adapted from the water well industry. Stainless steel well screens with a gap of 0.2 mm typically stop clay size particles with a small pressure drop. This screen is robust, straight, and strong enough to be incorporated in the drill without support structure. For ice drilling applications a special version of the screens was made. The filter provided reliable chip/fluid separation during deep-drilling operation.

To use the drill for rock coring, the structure of the instrument was modified. The top anti-torque, electronics, and motor-gear reducer sections remain the same as for ice coring.

One screen section was also used to filter out ice chips while permitting fluid to flow through the rock drill. A smaller Moyno pump, a core breaking hammer, and a core barrel stabilizer were incorporated into the drill. An industrial standard AQ thin kerf core barrel with a diamond bit (AQ bit OD/ID is 48/60 mm) was used for rock penetration (Wang et al., 1994). Since diamond bits require a high rotation rate (≥ 500 rpm), a 5:1 geared speed increaser was included in the rock drill section in series with the 17:1 ratio gear reducer. This was necessary to meet shaft fluid pressure seal PV limits for the sealed motor/gear reducer canister. Many of the drill components and special tools, such as the finger couplings, side reamer, and motor canister to name a few, were designed at PICO/UAF or at the UAF Geophysical Institute Machine Shop. Nearly all drill fabrication was done at UAF.

The drill control instrumentation

A navigation system was designed for the 5.2-inch deep drill in 1988 (Hancock and Koci, 1989; Hancock, 1994). The original purpose of the system was to inform the drill operator whether the drill was staying vertical and what the drill's orientation was relative to magnetic north. The microprocessor and digital converter had extra capacity and could accommodate additional drilling parameters, such as motor current, voltage, rpm, drill weight, fluid pressure, battery voltage, and several temperatures. The presence of the microprocessor in the drill made it possible to use a more powerful drill motor by controlling a reversing relay in the drill. This allowed the use of a high voltage AC current in the 4-km-long drill cable, thereby minimizing resistive losses and delivering more power to the drill motor.

The control panel at the surface was designed to be compact and light weight, and provide all the information and controls an operator needed to run the drill. It was designed around the same "computer on a chip" type microprocessor as was used in the drill. It did all the calculations on the data from the drill and also kept track of the drill depth by counting pulses from a shaft encoder mounted on the drill tower. Any drill parameter could be selected to be displayed on its digital readout. It was also designed to send all the data to a computer for logging. This feature later allowed a fast computer to display all the drilling parameters at once on a monitor screen while still logging the data.

The system was first tested at Dye 3 in Greenland in 1988 using a 1000-m cable. In 1989 the system was tested at Summit in Greenland, and in 1990 the 1000-m system was used to drill to 330 m using butyl acetate as the hole fluid. In 1991 a new winch and 4000-m cable were used. This required a redesign of the transformers using materials suitable for use in butyl acetate and a higher voltage because of the extra length of the cable. The higher voltage in the cable (1120 VAC) required that the signal conductors in the cable be shielded from the power conductors. The drilling proceeded to about 1600 m in 1991, but the Instrument Package seals had problems with the butyl acetate hole fluid. In 1992 the seals were redesigned and a new type of "O" ring grease was found that was resistant to the hole fluid, and the drilling proceeded to about 2200 m. In 1993 the hole was completed at 3053.5 m, and the system was taken to Antarctica where a new 1000-m winch was used to drill to 550 m at McMurdo Dome.

Borehole liquid

Environmentally appropriate drilling fluids were sought to support the deep ice coring objectives of the glaciological programs of the U.S. National Science Foundation (Gosink, 1989). In the past several decades, three types of fluids have been used for ice coring activities: l) fuel oil (DFA) usually containing several percent of a dense halogenated solvent; 2) aqueous ethanol or glycol solutions, and 3) and n-butyl acetate. Each has advantages and disadvantages. PICO/UAF conducted a chemical literature survey in an effort to identify a drilling fluid suitable for deep ice coring that would have the appropriate viscosity, temperature, and density characteristics, cause minimal potential health and safety risks for workers, cause minimal environmental impact, and maintain the highest integrity of ice core for scientific analysis. Of nearly 250,000 compounds electronically surveyed in the literature search, 11 potential drilling fluids were tentatively identified as suitable. N-butyl acetate satisfied most of the requirements (Gosink et al., 1991).

Cable

The GISP2 program was the first time a Kevlar® (aramid) electromechanical cable had been used for deep drilling. The weight reduction due to the 5-to-1 advantage in specific strength over steel offered significant savings in power and winch requirements as well as elongation advantages. Cortland Cable Hi Wire® conductors were chosen as power and data communication conductors. Construction was four #20 shielded wires surrounded by ten #18 conductors to supply power to the drill. The conductor bundle was surrounded by a double-layer woven Kevlar® strength member. The tested breaking strength of this cable was 22,200 pounds (10,000 kg).

The suggested minimum sheave diameter allowed with this type of woven strength member was 75 cm or thirty times the cable diameter, and the working load limit is 1000 kg. The drill was operated above the limit of both, as the actual sheave diameter was 63.66 cm or 28.5 times the cable diameter, and the working load was 1360-1500 kg. Kevlar® has a high abrasion resistance but not when rubbing against itself. In general, any low-temperature drilling fluid dissolves and removes lubricant provided with steel or aramid-reinforced cables. This resulted in an abrasion-induced loss of tensile strength in the first aramid cable.

Most electromechanical cables are used for borehole logging and generally are not subjected to the number of sheave- and load-induced bending and tension cycles associated with ice core drilling while immersed in a strong solvent. Thus, little information on abrasion damage was available about Kevlar® cables used for long-term ice coring operations. It is known that this type of failure can occur under similar operating conditions in sea water. Since 10,000-kg breaking strength is near to maximum for a double-layer construction, the alternatives for obtaining higher breaking strength are increased sheave diameters, a lighter drill, and different cable designs. Limiting cable use to 2000 m of drilling is another possibility. A cable design approach that was successfully used on the Taylor Dome borehole involved the use of four-layer unidirectional lays of Kevlar® with no weave in the structure. No cable lubricant was required, and no abrasion-induced cable damage was noted during drilling. After-project tensile tests have not yet been run to determine actual residual cable strength.

The drill performance

Major performance characteristics of the drill are shown in Figure 1. During four summer seasons, the deepest (3053.5 m) glacier borehole was drilled near the summit of the Greenland Ice Cap. The full potential of the drill was demonstrated during the second half of the third season and during the final season, when the depth of the hole doubled and rock core was recovered. The GISP2 ice coring was conducted with an average penetration rate of 240 m/wk. Maximum penetration rate of 45 m/day was reached when the hole depth was about 1750 m. Perhaps new deep-drilling projects can be done with a penetration rate close to 300 m/wk. Technical problems related to concurrent development of the drill used on the GISP2 project caused delay of the project completion. Every element of the drill was originally designed and built specifically for the GISP2 project. For instance, in order to obtain the best possible quality of ice core, extra time was spent to find proper geometry for the cutters. Significant time was also spent in the search for the best drilling fluid. Therefore, the completion of the GISP2 drilling project had another realized goal: proof test of a new and environmentally safe ice core drilling technology. That both the technology development and the ice core recovery programs were conducted simultaneously and successfully is indicative of the tremendous effort put forth by PICO/UAF personnel.

After preliminary tests of the industrial rock coring bit and core barrel under laboratory conditions to determine power and bit weight requirements, the rock drill section was designed and used for rock recovery from the bottom of the GISP2 deep borehole. After four drilling runs, six pieces of crystalline type rock core were recovered. Total length of the rock core recovered from the borehole was 155 cm.

Conclusions

Now that deep drilling in Greenland and an additional project at Taylor Dome, Antarctica, are complete. it may be stated that the PICO/UAF drill demonstrated an ability to penetrate thick ice sheets, recover high-quality ice core, and obtain bottom geologic samples. The analysis of the drill performance during the GISP2 and Taylor Dome projects allows proposed modifications which permit use of a lighter, faster, and more efficient drill in future ice coring research projects.

There are two factors which limit core recovery rate: (1) hydrodynamic drag-limited drill-lowering/raising rate and (2) surface handling of the drill components, ice core, and ice chips. Another important operation which consumes a lot of time in the field is setup of the equipment (see Table 1). For maximum cost-effectiveness of the drilling equipment, it should be possible to modify the drill for greater simplicity and lighter weight.

The first change would be in the drill/borehole geometry. Increasing the clearance by 3 mm radially should allow the lowering/raising speed to be increased by about 50%. A new 15-cm inner core barrel, drill centralizers, and modification of the coring head are the only requirements. It may also be possible to eliminate the outer barrel and replace it with tubes or simply to flush the drill fluid through the core barrel. Both of these modifications would allow significant reduction in hydrodynamic drag of the drill as it is pulled through the borehole. Potentially, this increase in transit speed could bring the core recovery rate up to as much as 450 m/wk.

Shortening the drill by one screen section (6 m) and reducing the core barrel length to 3 or 4 m may allow an additional increase of lowering/raising speed by about 10% due to reduced drag. The shorter drill would also require a shorter tower and lighter surface handling equipment. The deep-hole drill rate would be reduced somewhat due to the shorter core barrel, however.

The current drill motors could be replaced by lower inductance motors to minimize arcing and brush wear at the commutator. New motors should also have mechanically attached magnets and an epoxy type winding varnish to minimize chemical attack while operating in n-butyl acetate in the event that the motor canister seals leak. Further work is also needed on lubricant-free or ceramic bearings. A more permanent solution is to use brushless DC motors with an electronic control package. This is a costly fix, however.

Because this is a new drill system that has only been set up and used for two projects, many small incremental changes to the system can yet be made. Each of these changes could save field time, and their cumulative effect would be significant.

Acknowledgments

The successful accomplishment of the GISP2 deep-drilling program was possible because it was a five-year collective effort of the entire PICO staff. A combined and integrated effort was needed to solve the interdependent technical, logistical, and organizational problems. A technology development program and a major field science project were carried out simultaneously under very difficult conditions. New ground was broken in ice core drilling technology, and a 3,053.5-m fully cored borehole was completed at the summit of the Greenland Ice Cap. This work was performed under Contract

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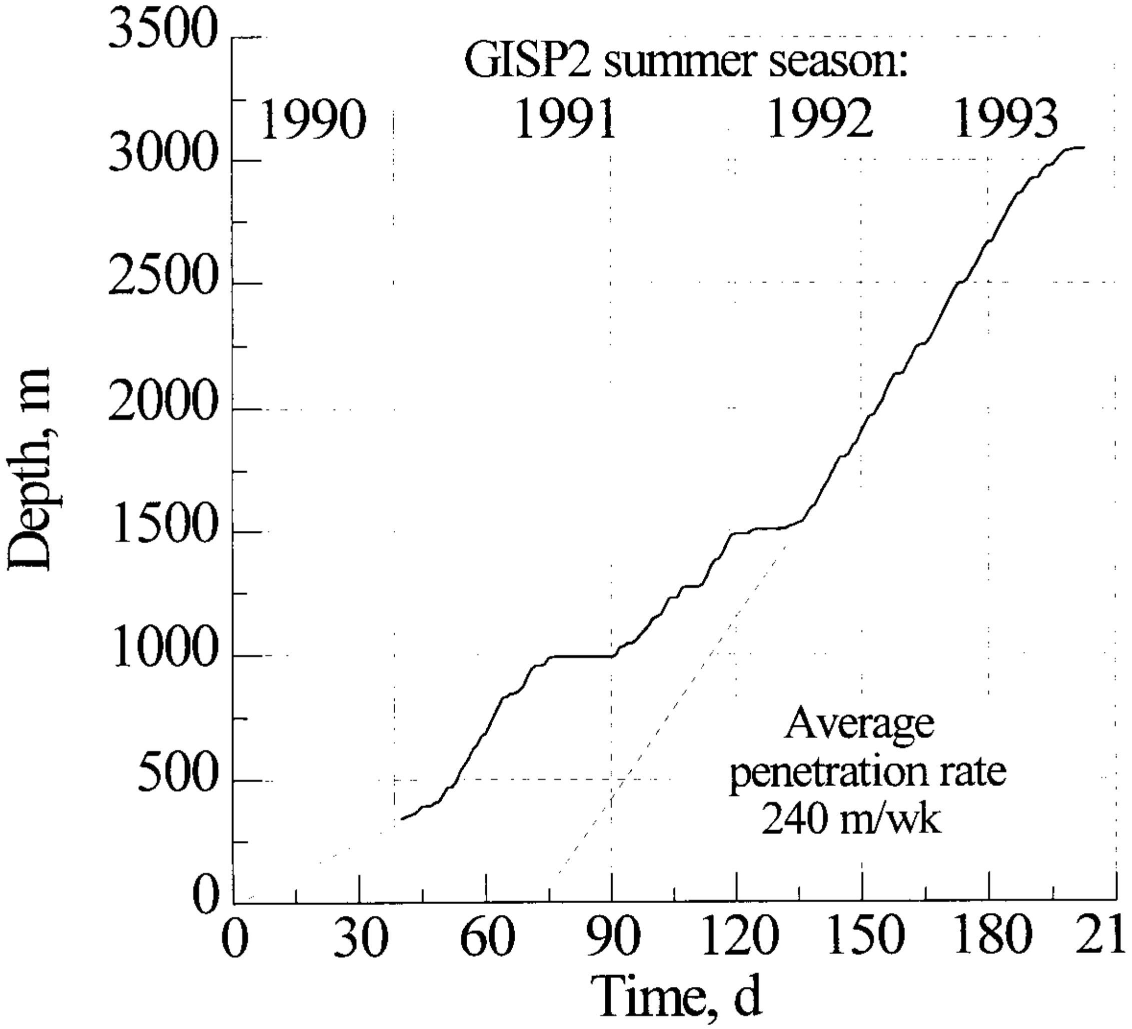

Figure 1. GISP2 ice core production.

Table 1. PICO electromechanical drill specification.

Depth (max.), m	>4000
Temperature, ^{o}C	0...-60
Environmental impact	small
Precautions	respirator, suit, +
Penetration rate (1000 m, 24 hr), m/week	200-300
Lowering/raising rate, m/s	0.45/0.55
Length: drill/core, m	~27
Power drill/surf. equipment, kW	3/30
Diameter: core/hole, mm	132/181
Silty ice/rock coring	YES/YES
Operation area (shelter), m^2	~300 m^2
Mounting time, hr/crew	120-180/6
Personal (1 shift)	4
Weight (drill+surf. equipment) kg	41,000
Drilling fluid requirements, kg/depth, m	48,000 (52,000 L)/2000