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An Engineering, Environmental and Logistical Analysis of the Polar Ice Coring Office 13.2 cm Ice Coring System

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An ice coring system may be defined as a thermal or mechanical system for retrieving ice samples in a continuous sequence to varying depths through glaciers or ice caps. Unfortunately, such a succinct statement doesn't begin to cover the difficulties involved. The nature of the mission dictates that the quality of the ice sample obtained must be as high as possible. Typical project locations are extremely remote, high in altitude and polar in climate. Transportation requirements are such that the system must be as light weight as possible, set up as quickly as possible and deliver as much ice core as can be obtained in the shortest possible time. The engineering difficulties involved in design and operation of such a system are affected by required sample size, ice temperature, environmental considerations, drilling rate and overall drill depth among others. The 13.2 cm drill designed by the Polar Ice Coring Office has been affected both conceptually and operationally by all of these considerations.

The requirement for developing and maintaining such a specialized system may seem somewhat esoteric on initial consideration, but further reflection provides ready justification. The data to be obtained from the study of ice cores provides a remarkable look into the Earth's paleoclimatic past. A variety of parameters are available for examination through analysis of the snow deposited as much as 200,000 years ago or more.

Yearly snow accumulations from times past have been buried by subsequent annual depositions on glaciers and the large ice caps such as Greenland and Antarctica. These yearly depositions are left in a layered, time-sequenced stack which readily lend themselves to dating. As the annual snow layer is buried under subsequent year's deposits, the increasing overburden pressure eventually squeezes it into the form of ice, locking within its crystalline structure the sampled secrets of a prehistoric atmosphere. These secrets are recovered by the ice coring drill and unlocked by the scientific analysis performed on the core itself.

Among the remarkable data parameters to be had in this endeavor are such things as atmospheric composition, climatic temperature ranges, precipitation accumulation rates, dust evidence of volcanic eruptions or large meteor strikes and even solar flare occurrences. It is even possible to recover micro-meteorites from the ice sample and the ice cuttings. It is apparent that possession of such an accurate data record extending that far into the past can provide immeasurably important comparisons with today's climate. Atmospheric effects due to man's activities on this planet should show readily on the long term record, leading to specific determinations with regard to such things as the greenhouse effect, solar warming and other pollution or energy driven phenomena.

Thus the justification for ice coring systems with regard to scientific data collection is an easy one to make and has resulted in a variety of different systems being designed, fabricated and field tested. Ice coring drill systems come in three basic types at present; thermal systems, dry hole mechanical systems and fluid-filled borehole mechanical systems.

Of the three, thermal systems are by far the simplest and easiest to field. The downhole portion of a thermal system consists of little more then a hollow core barrel with a resistance-type electrical heating element positioned on the open downhole circumference. Power is supplied from a surface generator down the drill cable to the heating element. This device simply melts its way into the ice under its own weight, carving out a cylindrical sample which is left in the core barrel. Once the barrel is full, a surface winch pulls upward on the drill. Spring-loaded teeth (core dogs) in the barrel just above the heating element then swing out and dig into the core sample, holding it in the core barrel and allowing the winch to break it off for retrieval. While the thermal drill has the advantages of being lightweight and simple, it is typically limited it to fairly warm ice (-15 C or warmer), and it can sometimes thermally shock the ice core, leading to crazing or large-scale fracture.

Dry hole mechanical systems eliminate both of the above drawbacks but as might be expected, generate new ones. This type of drill has an electric downhole rotary motor and cylindrical cutting head attached to the lower end of the core barrel. Thermal melting is not required since all ice removal is done with a mechanical cutting action. The generated chips have to be caught by the drill and removed from the hole along with the core. The same surface generator and winch are required as for the thermal drill and core dogs trap the core in the barrel in the same way. This type of drill is not ice temperature limited and does not thermally shock the core, but definitely seems depth limited by the nature of the dry borehole in the ice. 150 meters below the firn ice transition seems to be a typical depth at which core quality begins to seriously deteriorate. Why this occurs and why the depth at which it occurs varies somewhat with ice conditions is not entirely understood. Since the hole is dry, this drill type should also be further limited in terms of core quality with respect to depth. At some maximum depth a dry hole will begin to close due to overburden pressure. Core quality deterioration occurs at a shallower depth then would be expected from overburden pressure hole closure however, therefore this particular limiting aspect typically does not get a chance to occur. Mechanically this drill is substantially more complex then the thermal type and is also quite a bit heavier. It does not suffer from the logistics problems of providing drilling fluid however.

The third drill system in use and the one which addresses all of the listed problems is the fluid-filled borehole mechanical drill. The PICO 13.2 cm coring drill is an example of this type. In many respects it is quite similar to the dry hole mechanical drill. The major addition is the use of a drilling fluid nearly filling the hole. The drilling fluid performs three basic functions. Primarily its static head pressure serves to hold the borehole open against ice overburden pressure at great depths (> 500 meters). Secondarily it provides a readily pumped liquid transport medium for ice cuttings, allowing them to be trapped within the drill and removed from the borehole with the ice core. The fluid also contributes to higher core quality in ways which are not entirely understood. Since the ice is under great overburden pressure at depth, retrieving it upward through the fluid provides a moderating pressure gradient which helps the core to adjust to atmospheric pressure at the surface. There is apparently also a little understood mechanism of lubrication, molecular pore filling or other phenomena which contributes to better core quality as well. This effect has been seen in fairly deep boreholes in which the drill was only just covered with fluid, and the fluid pressure gradient did not effectively exist.

Interdependent Problem Set

A description of the interrelationships which exist between the engineering, environmental and logistical aspects of a large ice coring drill system is not easily accomplished, given the complex reliance of one requirement on the other. The engineering design and science needs are such that the highest quality ice core possible must be produced. A second typical requirement is that the largest possible ice core also be produced. Conversely, this must be accomplished in the shortest possible time, preferably with the smallest amount of equipment and personnel. Minimal impact on a pristine Arctic, Antarctic or high Alpine environment must be achieved while simultaneously accumulating the maximum amount of scientific data from within the ice cap itself in the short time dictated by season length and available funding. The extreme conditions of the environment also dictate engineering requirements to the extent that all parts and mechanisms must be able to withstand the very low temperatures likely to be encountered. They still must function at an optimal rate while providing the minimum in logistical problems such as weight, basic transportability and number of required spare parts. Given the above list of sample interrelationships, the nature of the design problem quickly becomes obvious. The competing interests all to often run counter to one another yet all must be optimized to the greatest extent possible.

Another aspect of the problem which must be taken into account is the "ripple effect" which occurs whenever one component of the system is modified. The problem here is that a small change in one area can easily produce a veritable tide of cause-and-effect situations which ripple throughout the design, causing major dislocations of a heretofore balanced system. The very nature of the competing requirements and their often inverse relationships makes the resulting outcome quite difficult to predict. When this aspect of the situation is combined with the disparate logistical, engineering and environmental requirements, a quite difficult problem set emerges.

Conceptual Design of the 13.2 cm Ice Coring Drill

The detail design of the PICO 13.2 cm ice coring drill addresses as many of the conflicting design requirements as possible. It should be born in mind though that this drill system is still evolving and a substantial portion of the learning curve has yet to be traversed. A point-by-point description of the entire 25.5 meter downhole length of the drill starting with the cutting head and moving upward will illustrate the system/requirement integration.

The cutting head is the business end of the system and is attached to the inner core barrel. Typical head dimensions are 17.75 cm outer diameter, 13.7 cm inner diameter and 15.25 cm in length. The head is also the rotational stabilizer for the lower end of the drill and carries a brass bushing which runs against the outer barrel inner diameter. The head carries the cutters and shoes and provides the actual shaving action which removes ice chips and carves out the core to be retrieved.

The cutters used to date have been of both the chevron and flat variety. It has been found that the flat type provides a coarser ice chip which is more easily handled for retrieval and also seems to provide a better ice cutting action with lighter bit weight. This enhances drill stability and minimizes vertical deviation of the borehole. Typically the cutters are angled at 45 degrees. Shoes are provided which allow either a 0.8, 1.0 or 1.2 degree angle of cutter bite into the ice, with a typical penetration rate of 1.0 cm per revolution. The cutters are typically made of tool steel. Carbide has been used successfully, but tool steel provides a good cutting edge, is easier to handle and is more cost effective. The head is driven at a typical rotational speed of 100 RPM.

The inner core barrel is steel though filament-wound carbon fiber has been used successfully. While the natural minimum stickiness of carbon fiber barrels enhances core quality, the change to steel was made in order to minimize head attachment problems and shift the operational center of gravity of the drill down nearer the head. The original carbon fiber inner barrels also had spiral flutes as an integral part of their outer wall. These rotated against longitudinal strips attached to the inner diameter of the outer barrel and were meant to perform two functions. They were supposed to enhance the pumped flow of the drill fluid carrying the ice chips and were also meant to center the inner barrel within the outer barrel. Field experiments with a smooth inner barrel without spirals have demonstrated that the flow capability of the pump is sufficient to carry the chips to the screens without use of the spirals or the fluid shear action of the strips. At present two core barrel lengths are used; three meters and six meters, with the six meter barrel being the standard. The inner barrel has an inner diameter of 13.7 cm and a wall thickness of 0.317 cm. Since the inner barrel carries the cutting head it must also carry the rotational torque from the drive motor.

The outer barrel is also steel, with an inner diameter of 15.71 cm and a wall thickness of 0.71 cm. It does not rotate, but serves to channel the drilling fluid flow carrying the chips up to the screens. Since the spirals are no longer used, the lower end of the outer barrel also serves as a stabilizer for the rotation of the head on its bushing, in effect a bearing race. The outer barrel also is made in six and three meter lengths, with six meters being the standard.

Immediately above the core barrels is the pump section. A progressive cavity type pump with a Teflon liner is utilized to move the drill fluid in a flow cycle from the cutting head, upward between the core barrels, through the pump, into and through the screens and back down between the outside of the outer core barrel and the borehole annular wall to the head. The ice chips (or cuttings) are carried on this flow cycle and trapped in the screens. The type of pump used is quite heavy but handles the ice chip flow through its pumping cavity well. The pumping rate is typically about 3 liters per minute at 100 RPM and about 0.5 HP is absorbed.

Immediately above the pump is the screen section. This simple device serves as a strainer to catch the ice chips that flow up through the pump. It consists of a hollow cylindrical tube whose wall is fabricated of screen material. The screen mesh will only allow ice chips of 0.02 cm width or smaller to escape. Two screens are typically used with the six meter barrel while a single screen is used with the three meter barrel. Each screen is six meters in length. A drive shaft from the motor section above the screens runs the length of the screens through the center and drives the pump.

Rotary torque is supplied to the cutting head and pump from the motor and gear reducer section above the screens. A 5 HP DC motor provides the torque through a 17:1 gear reducer. The motor typically runs at 2,500 RPM. Excellent success has been realized with the gear reducer, but substantial problems have been encountered with the motors. They provided very poor field performance when immersed in the n-Butyl Acetate drilling fluid. Only about 20 hours of running time was realized from each motor. To eliminate this problem, a high pressure seal package was designed to prevent the drilling fluid from entering the motor cannister. The seal package is designed to prevent drill fluid from entering the motor cannister at pressures as high as 4,500 psi.

Measurement of downhole drilling conditions is provided by an instrument section mounted just above the motor cannister. Parameters measured include temperature, pressure, bit RPM, drill motor current and amperage, two-axis inclination, azimuth reference, bit weight and depth.

These outputs are displayed on a data panel at the surface drill control station.

Just above the instrument section is the transformer cannister. For purposes of efficiency, power for the drill is transmitted down the drill cable in the form of alternating current. It is transformed to DC prior to powering the instrument section and drill motor.

In order to hold the entire 25 meter length of the drill against the rotational torque of the motor, anti-torques are installed above the transformer section. There are two sets of four of these and they are made from spring steel flat stock. As the drill enters the hole, these springs are radially compressed and take a grip on the borehole wall. Initially problems were encountered with the springs not being able to hold against full motor torque. This situation was overcome by stiffening the springs and by making their pre-set tension adjustable. No further problems of any magnitude have been encountered since the re-design.

An industrial S-type strain gage weight indicator is attached to the drill above the anti-torques. Read-out from this instrument provides bit weight and winch load readings to the instrument data panel.

The drill cable itself is a state of the art device capable of doing several things at once. It provides four power leads downhole to the drill as well as carrying six data channels back to the surface for drilling parameter read-out. It is sheathed in Kevlar 29 which provides it with an ultimate pull strength of about 106,750 newtons. Other inherent advantages of this particular type of cable is its minimum stretch under load, its minimum thermal coefficient of expansion and its very high resistance to chemical attack. Tests of the Kevlar 29 material which had been soaked for extended periods of time in n-Butyl Acetate showed a one time reduction of cable strength of 4%. Of course this cable is also substantially lighter weight for its strength then would be a steel cable of the same strength.

The surface handling equipment for the 13.2 cm drill is fairly straightforward. A diesel-hydraulic winch has 4 km of cable spooled on its drum. The winch is capable of pulling 11,000 pounds. A thirty one meter tower allows the full length of the drill to be hoisted from the hole. Depth encoders are attached both on the winch itself and on the tower crown blocks for redundant depth readout. A second weight-indicating load cell is also installed on the crown blocks.

Since the drill is designed in such as way as to allow it to be broken into approximately six meter sections, a rotating carousel has been provided on which to hang these individual parts. The carousel has eight stations. After a drilling run, the drill is hoisted completely free of the hole. Then the lowest section, the core barrel with included ice core sample, is removed and hung on the carousel. Following this operation, the two screen sections with their loads of ice chips are hung individually on the carousel. Two empty screen sections already hung on the carousel are then rotated into position and placed in the drill string. Finally an empty core barrel is attached and the drill is ready to make another trip downhole. As the drill is descending, the chips are cleaned from the two screen sections just retrieved and the core sample is carefully removed from the core barrel.

Removal of the ice core sample from the core barrel entails gently winching the six meter core barrel down to a horizontal position on a specially designed tray, winching off the outer core barrel, and then carefully pushing the core sample out of the inner barrel with a long "swabbing" rod. The core is pushed out of the barrel on to a roller tray. Sawing of the ice core into approximately one meter sections for handling then takes place. The inner and outer core barrels are then reassembled within one another, the cutting head, shoes and cutters are inspected and serviced, and the core barrel assembly is re-hung on the carousel. The surface handling system is now ready for the arrival of the drill from the next coring run. All of this typically takes place in about twenty minutes as the drill is descending on its next trip.

When the ice chips are cleaned from the screen sections, a vibrator is used to shake the compacted cuttings free and cause them to fall out of the open bottom end of the cylindrical section. The chips are soaked with n-Butyl Acetate and are carrying a fairly large amount of the drill fluid with them. In order to prevent any spillage and recycle the butyl, a drip pan is provided beneath the carousel. It serves to catch all of the drips and spills as the drill exits the borehole. All liquid butyl is funnelled back downhole. Additionally, an auger system is installed at the bottom of the drip pan. Its function is to carry the loose ice chips outside the drill shelter to a large centrifuge. There the cuttings are centrifuged until approximately 95 % of the n-Butyl Acetate with which they are soaked is recovered. This butyl is then funnelled back down hole as well. Approximately 5% of the drilling fluid is lost to evaporation.

n-Butyl Acetate is certainly not a traditional fluid for use in ice coring. The commonly used fluids in the past have been such things as Diesel Fuel Arctic weighted with fluorocarbons and LVT-200 weighted with bromoil. After a rigorous and thorough search, n-Butyl Acetate was selected as the drilling fluid of choice for its benign environmental and health effects, low viscosity, low freezing temperature and its autodense properties.

The entire surface portion of the 13.2 cm drill is typically enclosed in an unheated wind shelter though depending on conditions this is not a requirement.

Operational and Logistical Aspects of the 13.2 cm Drill as a Solution to the Interdependent Problem Set

Typical deep ice coring systems to date have usually limited themselves to taking a 10 cm diameter ice core sample. This volume of sample often proved insufficient for the desired scientific analysis. Therefore the 13.2 cm drill was conceived with the idea of providing a 70% larger sample retrieval capability.

Relatively short season lengths, particularly in Antarctica, place severe limits on the amount of ice with regard to depth that can typically be retrieved. The 13.2 cm drill has been designed with a six meter sample length retrieval capability for maximum retrieval rate. A three meter core barrel was initially used and worked well, but the six meter barrel allows a definite improvement. The three meter section still has its place however. Occasionally the anti-torques will still lose their grip on the borehole wall and be spun by the drill motor rather then its rotating the cutting head. This results in an enlargement of the borehole diameter and an inability for the anti-torques to resume their grip on the borehole wall. When this occurs, the drill is retrieved, the six meter barrel is replaced with the three meter barrel, one screen section is removed from the drill string, and the shortened drill is sent back downhole. This drill string length reduction effectively puts the anti-torques well below the point at which the borehole wall diameter was inadvertently enlarged. They are then able to resume their grip on the borehole wall and drilling proceeds for one three meter run. After this run, the six meter barrel and screen section are placed back in the drill string.

As was mentioned earlier, the ice chips removed by the cutting head must also be removed from the hole. The pumped drill fluid flow path accomplishes this with the help of the screen sections. The design was executed this way in order to minimize the equipment requirements for logistical purposes. Otherwise a large surface pump, a complete downhole-surface circulation system and a surface screening system would have been required.

It is for this same reason that the drill was conceived as a cable-suspended device rather then a more traditional surface-driven rotary system. Overall weight and parts requirements were minimized.

Relatively severe problems with drill motor life occurred with the 13.2 cm system in its second year of deep drilling. It was found that the drill motors were only averaging approximately 20 hours of running time before failure. The motor failures were typically attributable to severe material surface removal occurring on both the brushes and the commutators. Secondary damage was appearing in the forms of magnets coming loose due to having their retention adhesive dissolved and chemical attack on the motor winding resin. While it was difficult to pin down the exact problem at the brush/commutator interface, the chemical attack on the magnet adhesive and winding resin was due to the very active chemical nature of the drilling fluid, n-Butyl Acetate, which is a relatively strong solvent. Butyl was finding its way into the motor cannister due to an improperly designed seal. Damage at the brush/commutator interface was traced to three possible sources;

(1)Hydroplaning of the brushes in the liquid butyl, which caused their clearance from the commutator to be too great, leading to arcing.

(2)Dissolution of the winding resin which allowed a chemical build-up to occur at the brush/commutator interface, again leading to arcing.

(3)Dehydration of the brushes due to immersion in butyl, which removed all the lubricating water from the brushes, leading to severe erosional wear at the interface.

(It was also initially thought that wear of the original carbon fiber inner core barrels might be generating enough highly conductive carbon fiber particles in the drill fluid to cause arcing at the brush-commutator interface. This did not turn out to be the case.) Previous motor tests in butyl had indicated that the principal failure mode should be bearing failure due to butyl having dissolved and washed out all of the bearing lubricant. This typically occurred at approximately 80 to 100 hours and the previous season's experience had born out these test results. Given the difficulty of determining the exact problem, a multi-contingency solution was implemented. The seal design of the motor cannister was substantially changed to minimize the possibility that any butyl might enter. New brushless DC motors were procured which should be capable of running immersed in butyl without damage. Several different brush formulations were procured for use with the existing motor. These were expected to be chemically inert when immersed in butyl.

The only other serious problem which has occurred with the system has been the winch. In order to be able to drill the deepest ice on the planet, as has been planned for the 13.2 cm ice coring system, at least 4,000 meters of cable were needed. This calls for rather a large winch. Yet at the same time, its size and weight must still allow it to be readily field transportable. A hydraulic drive system with a separate prime mover was chosen. This winch was specified primarily for its capability to do the heavy work of hauling the 1,500 pound drill and its cargo of ice core up and down a deep borehole many times. However the finer control requirements such as precise bit weight, payout control and slow speeds for making connections were not available with this system. Therefore it has been found necessary to modify the winch with the addition of a penetration drive. This drive provides the fine low speed control needed for handling the drill on the surface and for drilling as efficiently as possible with the greatest control. Problems such as cutter wear, hole vertical deviation and core quality are thus addressed. A secondary problem with the winch was the appearance of a relatively severe hydraulic fluid leak in the winch motor. This leak was a direct result of the extremely low temperatures inherent at the drill site. The hydraulic fluid viscosity had increased due to an unwarmed case drain and the motor shaft seal was a non-arctic grade type. This combination of circumstances resulted in seal failure. Due to the remote location and environment, it was not possible to repair the leak in the field. As the season progressed, the leak worsened until reasonable control of the winch was lost, resulting in high bit weights and a vertically deviated hole.

Perhaps the single aspect of the system that has the greatest effect on its function is the use of n-Butyl Acetate as a drilling fluid. Its disadvantages are several; it quickly chemically attacks nearly all hydrocarbon compounds other then Teflon, butyl rubber and a few others, it is worthless as a lubricant, causes high mechanical wear and dissolves existing lubricants, it is a mild narcotic in large concentrations, requires special handling and exposure procedures and it is relatively expensive. On the other hand it is auto-dense with regard to temperature, does not contaminate the ice core analysis, will not freeze until a temperature of -78 C is reached, has a relatively low viscosity, is non-toxic within reasonable exposure limits and most importantly, is environmentally benign. Even at very low temperatures it evaporates and biodegrades readily, much more so then traditional drilling fluids used in the past.

Transportability is as important as any other requirement for a system like this one. After all, if the drill cannot be readily delivered to the drill site it is of little use. Everything which comprises the system is modular and as lightweight as the drilling engineering requirements allow. The 25 meter length of the drill breaks down into sections no longer then six meters. The tower sections are 3.5 meters in length. No section of the carousel exceeds 7 meters. The entire system breaks down into pieces which are of a weight that allows them to be carried by one to four people. The only part of the drill system which cannot be moved by individuals is the winch and prime mover. A snow cat is required to tow either of them on their skids. The entire drill can be readily moved with the use of Hercules LC-130 ski-equipped cargo aircraft. By far the heaviest component of the system is the n-Butyl Acetate drilling fluid. A deep hole can require 350 drums or more.

Future Design Aspects of the 13.2 cm Ice Coring System

The PICO 13.2 cm drill system was originally designed for a specific project; deep ice coring in Greenland. The relatively long Greenlandic summer (four to five months of useable time) had a great deal to do with the initial design of the drill. Deep coring projects in Antarctica are scheduled to follow, but the useful field season there is substantially shorter (typically no more then three months). Logistical problems in Antarctica are also compounded by the large number of projects that are in competition for the relatively scarce use of the LC-130 aircraft. With these parameters in mind, design modification considerations are under way for the 13.2 cm drill.

The typical deep drilling project in Antarctica is not as deep as the 3,200 meter Greenland project. Typically boreholes will be on the order of 1,000 meters depth. This fits well with the shorter Antarctic season since for the sake of economics it is desired to finish each deep coring project in one Austral summer if at all possible. To this end the 13.2 cm drill is being examined with an eye toward optimization of its capabilities for this depth and this length season. Of course it is most desirable to accomplish this while making as much use as possible of the existing drill components.

One option being examined is the shortening of the drill length in order to lighten the downhole portion as much as possible, thus minimizing the winch requirement and matching the surface handling time as closely as possible to the maximum trip time. This would entail nothing more then use of the existing three meter barrels and an existing 1,000 meter winch. An interesting ripple effect would be a tower requirement ten meters shorter then originally needed. This is beneficial in terms of transportability, set-up time and undesirable wind effects sometimes encountered when the drill is hanging on the tower. A lighter weight drill fluid pump is also being examined.

Another possibility being considered is complete elimination of the tower. The carousel would still be used but the drill would not be hoisted free of the hole in order to break section connections. It would hang in the hole and be disassembled from the top down rather then from the bottom up, as is typically done with geologic drill systems. The danger of course is the possibility of accidently dropping a portion of the drill downhole. While this is certainly a possibility, this particular handling system is used world wide for oil and gas drilling every day and has been for many years.

It is even possible to eliminate the carousel itself. One needs only to drill "rat holes" ten meters deep in the snow surrounding the borehole, line them with fiberglass pipe, and make use of them as convenient receptacles for holding the different drill sections as the section connections are broken from the top down. A swinging arm like a jib crane would suffice for drill section positioning purposes.

Elimination of the drill shelter is also under consideration. Methods of minimizing drifting while still providing some driller and control system protection from the elements are being evaluated. Again the advantage here is minimization of drill system set-up time.

Perhaps the most promising concept is reducing the drill fluid volume requirement as much as possible. Depending on drill depth, the drilling fluid accounts for a very large portion of the required transportation weight for the 13.2 cm drill system. A typical 1,000 meter borehole would need about 150 to 175 drums of n-Butyl Acetate. This is a very heavy and bulky requirement in terms of air transportability to a remote site. Options under examination include numerical studies to determine the minimum amount of fluid needed in a given depth borehole in order to hold the hole open against ice overburden pressure and the minimum fluid pressure gradient required to maintain high core quality.

One other future capability of the 13.2 cm drill should also be mentioned. The system was originally conceived with the idea that it should be capable of penetrating the till layer beneath glaciers and ice caps since this is one of the most scientifically interesting areas. The system was also meant to be able to penetrate bedrock beneath ice caps in order to retrieve geologic samples, hence its relatively high horsepower and bit weight capability. Tests in granite have confirmed that the drill has sufficient horsepower and bit weight to drive an AQ or BQ diamond rock coring bit and core barrel. This capability is under further design development.

As is readily apparent, all of the above effects and design aspects have a strong influence on the drill system's performance in the field. The drill must be capable of retrieving good ice core from great depths under the worst field conditions, yet must be durable, easy to use, light weight, modular and readily transportable. The PICO 13.2 cm deep ice coring system meets these requirements in most respects, although compromises are always required with conflicting specifications. The drill system is still evolving in some areas, particularly with regard to variable drill depths and season lengths. Further field experience, design and test will determine the final configuration (or configurations) of the system for optimal logistical, engineering and environmental ice coring operations.