Comparison of Ice Coring Options for the Antarctic Inland Core Project

National Science Foundation

Ice Core Working Group

6 March 2003

Alfred Eustes – Colorado School of Mines

Will Fleckenstein – Colorado School of Mines

Michael Gerasimoff- Ice Coring and Drilling Services

Curt LaBombard – Raytheon Polar Services

Don Lebar – Ice Coring and Drilling Services

Bill Mason – Ice Coring and Drilling Services

John Rhoades – National Ice Core Laboratory

Phil Robl – Physical Sciences Laboratory

Kendrick Taylor – Desert Research Institute

Mark Wumkes – Glacier Data

Contributing Authors

Charlie Bentley – Ice Coring and Drilling Services

Eric Cravens – National Ice Core Laboratory

Geoffrey Hargreaves – National Ice Core Laboratory

Todd Hinkley – National Ice Core Laboratory

Bruce Koci – Ice Coring and Drilling Services

Bruce Vaughn – University of Colorado, Boulder

SUMMARY

ICDS was given the task to evaluate options for a new US deep ice coring drill based on science goals and requirements outlined by the ICWG. A design team consisting of representatives from a number of organizations was formed to gather information and present options that included developing a US version of the successful European EPICA drill and a new drill (DISC drill) based on the lessons learned from the EPICA and other deep ice coring drills.

A basic assumption in the evaluation was that the science goals and requirements approved by the ICWG were to be used as the "yardstick" in the evaluation. The fundamental goal of the drill system is to extract science quality ice cores. The next US deep ice coring drill system must also protect the safety and health of those participating in field projects and the natural environment while keeping logistical needs and expenses within reasonable constraints. Core handling and basic logistics for each option was also assumed to be the same for each option considered.

The EPICA drill system is a tethered mechanical system first used by the Europeans in Greenland in 1995. The two versions of the drill being used in Antarctica during the 2002-03 season are fundamentally the same with some differences both in hardware and in operating procedures. Two ICDS engineers had the opportunity to serve on the crews at Dome C and DML during the 2002-03 season. Their experience along with a number of meetings and conversations with the Europeans and review of the literature form the basis of the evaluation of the EPICA drill.

The EPICA drill is a proven drill and has been successfully extracted excellent core to depths in excess of 3000 meters. Major features of the drill are

Drill BHA length: 11 m

Drill BHA weight: 197 m

Core diameter: 98 mm

Borehole diameter: 129.6 mm

Inner rotating core barrel with 104 mm OD and 100 mm ID

Outer core barrel with 118 mm OD and 113 mm ID

Core barrel length of 3.5 meters – core length normally 3 meters

Pump and drill rotation driven by single motor

Normal rotation speed of 63.5 rpm (varies from 50 to 75 rpm)

Bottom hole assembly power requirement: 400-600 W

Drill cable diameter: 7.33 mm

Titling tower for drill lay-down

Light weight

Drilling fluid is highly refined, deodorized petroleum solvent with a chlorofluorocarbon densifier

The design team's consensus is that the EPICA drill is underpowered. This results, along with other factors, in difficulty in coring in "warm" ice and in silty ice. In addition it doubtful that the EPICA drill can easily be adapted for replicate coring. Communications in the EPICA drill are judged to be inadequate and obsolete and would require a re-design if a US version of the drill were built. The drill cable, which combines conductors for power and data transmission, severely limits the rate of communication between the BHA and the surface.

Comparison of Ice Coring Options for the Antarctic Inland Core Project

Three EPICA options were considered for the US deep ice coring drill:

EPICA with minor modifications that would include updating the electronics and possibly making the components compatible with n-butyl acetate.

EPICA with moderate modification that would also include improving the control system, tilting tower, and cutter heads and adding fluid flow measurement.

EPICA with major modifications. This drill would entail re-designing the BHA and increasing the cable size. Changes would tend to cascade to the point that the drill would be completely new and was not considered further.

The EPICA drill was considered the “baseline” option for logistical requirements comparison.

The basic concept developed for the DISC is also a tethered mechanical drill based on the features of the EPICA, US 5.2-inch, the Vostok KEMS-132, and other drills. Its major features are

- Bottom Hole Assembly (BHA) Weight: 200 kg, assuming 3-meter x 100 mm core
- BHA Length: 9 meters
- Core Diameter: 100 mm
- Borehole Diameter: 15.3 cm (not optimized)
- Core Length: 3 meters – 6 meters
- Weight of Assembled Tower -- 1350 kg
- Bottom hole assembly power requirement: 3 kW
- Drill cable diameter: 1.57 cm
- A rotating outer barrel stabilizes the BHA and allows for improved cuttings transport.
- Separate and independent speed control of the drill motor and the pump leads to a more versatile coring parameter control.
- The separate motors also give the ability to pump the drill into and out of the borehole.
- A non-rotating inner core barrel will facilitate core orientation, allow for mechanisms to sleeve brittle ice cores for improved recovery, and can help reduce stresses in the core from rotation friction.
- Cutter speeds of 60 to 180 rpm are possible.
- The pump is “off-the-shelf”, has a large pumping rate, and is pumping clear fluid without chips.
- The BHA is relatively short and yet it will take 6m long cores.

The major advantage of the DISC drill is that it is not locked onto an existing development path and can incorporate features that help meet the science requirements. Many of these features have been used successfully on other ice coring drills. The major risk with this approach, however, is that the new design is unproven.

Two options of the DISC drill were considered, a 10 cm diameter core version and a 12.2 cm diameter core version. The two options would be expected to be essentially identical except for the diameter. The major advantage of the 12.2 cm DISC drill over the smaller one is that it allows more core for science.

The major disadvantage of the larger one is logistical, resulting from the increased amount of drilling fluid required and the greater core volume.

The EPICA drill is estimated to require a total of 24,100 gallons of drilling fluid for the coring of a 3800 m borehole along with sidetracks for deviation drilling. This would require approximately 12 flights. The 10 cm DISC drill would require 33,600 gallons of drilling fluid and require about 16 flights. The 12.2 cm drill is expected to require 47,100 gallons of drilling fluid and would require approximately 23 flights for a 3800 m hole and sidetracks. The EPICA drill and 10.0 cm DISC drill are estimated to require approximately 113 of the proposed HD (high density) containers and 6 flights for core while the 12.2 cm DISC drill would require 150 containers and 9 flights.

Any drill constructed would be rigorously tested in Greenland prior to mobilization for science use. The test would be full-scale to check all aspects of drill operation and equipment. It would provide an opportunity to train drillers and replicate coring equipment and techniques. In addition, many components and systems will be tested in the United States.

Logistical and infrastructure support and core handling would be fully integrated into the design and operation of the drill systems and are expected to be the same no matter which drill option is pursued. Concepts are being developed to provide an extended drill season in order to reduce the number of seasons required for coring and on-site science activities. One concept is using prefabricated structures that are easy to set up and take down. The second is to use a smaller put-in crew to mobilize life-support and ski-way grooming.

If the on-site aspects of the Inland project can be completed in five years, the first year would be dedicated to setting up the infrastructure and staging the bulk of the fuel and drilling fluid as well as drilling, reaming, and casing pilot holes. During the second and third years coring of the borehole would be accomplished along with retrograding some core. Borehole logging and replicate coring would take place in the fourth year along with additional retrograding of core. In the fifth year remaining core would be retrograded and the camp dismantled. Peak occupancy of the camp is expected in the second year with 46 people.

The goal of the core handling process is to minimize the number of times the core is handled and moved at the drill site through the shipping process. Another goal is to reduce the number of flights needed to transport the core. Dense packing of the cores and the use of refrigerated mil-vans (ISO shipping containers) are being considered. Another objective of the core handling system is for information from the drill site database to be integration with the NICL database.

TABLE OF CONTENTS

BACKGROUND

PURPOSE OF THE REPORT

Deep ice cores are a treasure trove of scientific information. Since the GISP2 program, the United States has had a deep ice core rig for operations in fluid filled boreholes. In 2001, Ice Coring and Drilling Services (ICDS) commissioned Drs. A. W. Eustes and W. W. Fleckenstein, drilling engineering professors at the Colorado School of Mines (CSM), to assess the deep ice coring capability and options for the United States ice coring community. In the report, **United States Deep Ice Coring Rig Assessment** (Eustes 2001), a litany of woes regarding the United States deep ice coring capabilities were outlined. Unfortunately, the 5.2 inch rig used at GISP2, although originally fundamentally sound, has had difficulties in subsequent field operations. In addition, many recommendations were made regarding the development of a deep ice-coring rig. Based on the CSM study, ICDS recommended to the National Science Foundation (NSF) that another ice core drill be developed to replace the 5.2 inch drill. There are two options with various permutations. The two options are to buy an EPICA system as used by the European science community or build a new drill (called the Deep Ice Sheet Core (DISC) rig) designed with the lessons learned from the 5.2 inch, EPICA, and other deep ice core drills. The permutations involve the level of EPICA modifications deemed necessary and the diameter of a new drill. This report explores these options.

ICDS TASKING

As noted in the Eustes 2001 report, there were many performance problems with the 5.2 inch deep ice coring rig. The primary issues included a convoluted and time intensive set up and disassembly (mobilization and demobilization, respectively), the excessive time needed for running the wireline coring assembly (the bottom hole assembly) into and out of the hole (called tripping), and the surface handling of the core as it was pulled out of the hole and laid down horizontally. There were also problems with winch control, bottom hole assembly vibrations, barrel straightness, core bit and dogs, borehole fluid problems, and so on. There were also both domestic and field management issues and field conflicts between contractors in previous operations.

The Ice Core Working Group's task was to evaluate the options for the next deep ice core drill, especially for the upcoming inland coring program, but also for unnamed future projects. This evaluation was not limited to just the coring equipment hardware, but better ways to handle cores and to streamline the support camp and logistics train were considered. This report is the culmination of that task.

In May 2002, a team of scientists and engineers met to evaluate various designs of deep ice coring in the United States. This deep ice coring team consisted of people from the National Science Foundation; Desert Research Institute; University of California, San Diego; University of Colorado, Boulder; Ice Coring and Drilling Services; National Ice Core Laboratory; Glacier Data; and the Colorado School of Mines. Later, Raytheon Polar Services was brought onto the team. The inclusion of the scientific users, including the Chief Scientists of the Inland Core Project, as an integral part of the design team insured that the needs of the science community would be respected.

This team at the time of this report consists of:

Charlie Bentley – Ice Coring and Drilling Services – Principal Investigator
Eric Cravens – National Ice Core Laboratory – Assistant Curator
Alfred Eustes – Colorado School of Mines – Associate Professor, Drilling Engineer
Will Fleckenstein – Colorado School of Mines – Adjunct Professor, Drilling Engineer
Geoffrey Hargreaves – National Ice Core Laboratory – Curator
Todd Hinkley – National Ice Core Laboratory – Director
Bruce Koci – Ice Coring and Drilling Services – Lead Drilling Systems Engineer
Curt LaBombard – Raytheon Polar Services – Planning Support Manager
Don Lebar – Ice Coring and Drilling Services – Program Manager

Bill Mason – Ice Coring and Drilling Services – Lead Mechanical Engineer
John Rhoades – National Ice Core Laboratory – Assistant Curator
Phil Robl – Physical Sciences Laboratory – Lead Electrical Engineer
Kendrick Taylor – Desert Research Institute – Chief Scientist
Bruce Vaughn – University of Colorado, Boulder - Scientist
Mark Wumkes – Glacier Data – Lead Drilling Operator

This team spent significant time reviewing various options and considering the option permutations. The team reviewed the operations at GISP and Siple through videos, recollections, and documentation. Literature from the CREEL library and other places was researched, read, and archived. Two visits to the University of Copenhagen were undertaken, one for an engineering review of the EPICA and one to review potential cooperation efforts and economic estimates. Also, two of ICDS's top engineers, attended the Mousel, Germany meeting in late October 2002 on the EPICA. In addition, these same two engineers spent two months this past Antarctic season, operating the EPICA under field conditions at Dome C and Dronning Maud Land. The teamexamined various conceptual designs and their application in different scenarios.

ASSUMPTIONS

Some assumptions were made to focus the task. They are as follows:

1) There will not be a significant effort to accomplish scientific tasks on the cores in the field, as was done in the GISP project. The exceptions are those items that are time sensitive. The cores would be cleaned, relaxed, packed, and shipped to NICL.

2) The science goals as approved by the ICWG in November 2002 are fixed.

3) There would be one field season somewhere to test the rig and operational doctrines and train operators for any option selected.

4) The coring fluid would be n-Butyl Acetate, although other fluids, if possible, that meet the scientific and engineering specifications will be evaluated.

5) Once the core is laid down, the core handling is identical regardless of the option selected. This means that the logistics to support core handling are identical for any option selected and therefore the number of core handlers is identical for each option.

6) The number of drillers needed to handle a drill is assumed to be the same regardless of the option. This could be subject to plus or minus a person or two, but in general, any option would probably require three people, a lead driller/operator and two people on the floor to handle the surface equipment.

7) This means that since the number of people for core handling and rig operations are the same, regardless of the option selected, then the camp support for those people is the same, too.

GOALS

The *primary goal* of any design by the deep ice coring team is to *extract science-quality ice cores*. This is to be done as efficiently as possible with additional goals to minimize environmental impact, safeguard the health of participants, and keep logistical needs and expense within reasonable constraints. All decisions made with regard to coring equipment, operations, logistics, and management are made within the context of the primary goal.

There are four major aspects to any next generation of ice coring operation: the drill equipment itself; core handling and storage facilities; camp facilities; and logistical support including mobilization and demobilization. The integration of the design of these subsystems is essential if the goals of the prospective deep coring projects are to be achieved.

Another consideration of coring operations is the critical path, defined as_______. Anything that lengthens the time in the borehole or slows down surface turnaround time impacts the entire schedule. Anything that can be accomplished outside of the borehole will be off of the critical path and will at a minimum, neutrally impact the overall time. More than likely the net result is a reduction in time. These thoughts have helped guide the team in the decision process.

Another goal is to reduce the logistic support to the minimum required consistent with the science goals. The logistics requirements of the drill option, camp support, core handling, ice retrograde, and borehole fluid are under review. Although not fixed, the team is actively considering many options to reduce the logistic effort. Some of these efforts are discussed in subsequent sections of this report.

The team identified the primary driver of the logistics effort as the time spent in the field, especially number of seasons. In order to reduce the overall logistics effort, it is necessary *to shorten the time in the field*. A season saved significantly reduces the overall effort. Any investment that can make this happen, consistent with the scientific goals, is worthy of review and consideration. This reduction of field time also gets the ice cores into the scientific community faster.

Finally, other design goals for the team were to keep the equipment and operations simple, flexible, and modular.

Report Outline

This report is broken into the following sections. First, both the science requirements and a general description of all devices are described. Then three drill options are discussed, the EPICA drill, a 10 cm DISC, and a 12.2 cm DISC. Each discussion includes a descriptive section, history of the performance and problems encountered, the advantages and disadvantages with the risks and uncertainties for that option, the logistical effort for that option alone, and the resources needed to design, build, test, and field that option. After those sections, the aspects common to each option, the core handling, camp support, testing, and replicate coring methods are discussed. Finally, a concise discussion of each option, with permutations with the EPICA, are discussed and outlined.

SCIENCE REQUIREMENTS

GENERAL COMMENTS

The first step in the conceptual design phase of the ice coring system was the development of the science requirements. The purpose of the new drilling *system*, which includes the coring rig, operation procedures, core handling, camp, etc., is to obtain high quality ice cores continuously from the surface to a depth of at least 3,800 meters. The drill system should also to be capable of collecting replicate cores from areas of special interest. Other science requirements include the ability to core ice at the pressure melting point, to minimize the number of core fragments, and to determine the core orientation. To meet the science requirements, the cores must never exceed 0ºC at all times, exceed -2ºC for more than two minutes, exceed -10ºC for more than twenty minutes, and exceed -15ºC for an hour or more. Each 1 meter core will also have a single science and operational parameter data log. Another desired, but not required, science requirement is the ability to core the bedrock.

Listed below are the science specifications for a new deep ice core drill and core handling system. These specifications do not deal with the logistics, safety and operations issues that must also be considered. Some desirable specifications that are not firm requirements are also listed and are identified as such. The word “core” can mean many things. In this document “core” is all the ice recovered from the top of the hole to the bottom. A “core segment” is the ~1m long unit of ice that goes in a core tube for shipment and storage. A core segment may be made up of one or more separate pieces of ice. A "piece" of ice means a mechanically coherent block of ice without any internal fractures.

GENERAL REQUIREMENTS

Ability to continuously collect core to a depth of 3,800 m.

Ability to core in ice with 5% silt for a distance of 50 m.

Ability to drill in ice that is at the pressure melting point.

Ability to drill in ice that is at the pressure melting point without using antifreeze fluids. (This is desirable but may not be practical.)

Ability to drill at borehole temperatures as low as –60° C, and surface temperatures as low as –40° C. (This is desirable; firm requirement is borehole temperatures as low as –40° C, and surface temperatures as low as –30° C.)

CORE CHARACTERISTICS

Complete core recovery (100%) from top to bottom.

Ice pieces to fit snugly together without any gaps.

In non-brittle ice, the packed core should have no more than 12 pieces of ice per 10 meter section of core.

In brittle ice although, there may be many of pieces in a single ~ 1m core segment, the pieces must fit together and retain stratigraphic order. More than 80% of the ice volume must be in pieces that each have a volume >2 liters.

Ability to determine the *in-situ* orientation of core segments to within ±10°.

Core diameter to be >98 mm. It is desirable that it does not vary by >3 mm.

Core should not have any “healed fractures”, which cannot be seen but trap drilling fluid in the interior of the sample. “Healed fractures” probably form during drilling, take up drilling fluid, and subsequently seal-off and become invisible. The best way to avoid this problem is to not fracture the core in the first place.

Ability to know the drilling and core handling history of each core.

REPLICATE CORING

Ability to collect additional “replicate” core that is at least 8 cm in diameter over an interval that is up to 150 m long and within 0.10 to 20 m of the main borehole. The purpose of this capability is to multiply the volume of ice available for analysis across depth intervals of special interest. This would include, for example, rapid climate transitions that typically occur over <10 m of core. Most replicate cores will only be 30 to 40 m long.

Ability to collect replicate cores over at least five specified intervals.

The orientation of the replicate core is not important but needs to be known, and ideally should never be more than 15° off vertical.

DRILLING FLUID

Drill fluid to be evaporated from cores prior to packing so that it does not produce a hazardous vapor at NICL.

Drill fluid to be immiscible with water.

A index of refraction similar to ice (1.33 ± 0.06) is desirable.

Drill fluid must not interfere with high-vacuum mass spectrometry (for example, silicone oil interferes with mass spectrometry and other analytical techniques for measuring trace and major constituents in the ice and gas phases).

HOLE CHARACTERISTICS

Borehole diameter not to vary by more than 2% over 50 m, except for special conditions such as deviation drilling.

Borehole inclination <5° from vertical.

Hole to remain open and accessible to the bottom for at least 10 years after drilling. The diameter during these 10 years must be at least 8 cm.

Hole wall to be smooth enough for optical logging. (Current thinking is that this means a surface roughness of <0.3 mm plus removal of scars due to clamping marks. This is desirable but may not be practical.)

Inclination, azimuth, and diameter of the hole to be determined as a function of depth.

DEPTH MEASUREMENT OF DRILLING SYSTEM

Absolute depth measurement accuracy of 0.02% of depth.

Relative depth measurement accuracy of 2 cm over the length of the drilling run while drilling. (i.e. Ability to measure the length of core to within 2 cm while the drill run is underway.)

DRILLING INFORMATION

Recording of the following properties 10 times/second while drilling:

Depth, drill rotation rate, cutting torque, weight on bit, penetration rate, fluid temperature, core barrel acceleration. Measurement of core barrel flexing is desirable.

BEDROCK DRILLING CAPABILITIES

(The following abilities are desirable but should not be included if they significantly increase the cost of conducting the drilling operation.)

Ability to collect up to 4 m of bedrock core at least 1.5 inch diameter in a frozen and non-frozen bed.

Ability to collect 2 m of unfrozen unconsolidated basal material.

Ability to drill 20 m of sandy ice (5% sand) and through 1 cm rock pebbles.

CORE HANDLING

Ability to electronically image every core segment.

This imaging would be for curatorial purposes, and documentation of core quality. These images would not be suitable for stratigraphic analysis, which would require considerably more effort.

Ability to measure the length of each core to within 1 mm.

Surface temperature of the core after removal from the drill.

Core temperature never to exceed 0° C.

Core temperature never to exceed -2° C for >2 minutes.

Core temperature never to exceed -10° C for >20 minutes.

Core temperature never to exceed -15° C for >1 hour.

Core segments (i.e. packed units of core ready for shipping) to have a length of 90 to 101 cm when packed in ~1 m long core tubes.

Ability to know the drilling and core handling history of each core segment.

GENERAL DESCRIPTION OF ALL DRILLS

Several drilling methods were considered in addition to the tethered mechanical drill. They are discussed below after a description of the tethered mechanical drill. Overall, the tethered mechanical drill is the lightest and most energy efficient type of coring rig for the operations needed for ice. Therefore, the recommendation is to stay with this style of coring rig for deep ice coring operations.

TETHERED MECHANICAL DRILL

Most electromechanical ice coring drills follow the same general plan. Each design starts with a auger style of ice core bit, usually with three cutters and associated flights to carry the chips up to the fluid flow channel. The core breakers are integrated with the bit. There are two concentric barrels. The inside barrel receives the ice core and the annulus between the two barrels constrains the borehole fluid to flow with the chips into a screen section, above the barrel. There is a fluid pump that circulates the coring fluid to the outside of the drill and down the annulus between the borehole and the outer barrel. There is a motor that rotates either the inside (5.2”, ISTUK, EPICA, JARE) or outside (KEMS) barrel. Above the motor is the electronics package used to control the motor and to monitor borehole and assembly conditions. Above that section is an anti-torque section consisting of bowed leaf springs or skates that oppose the torque generated by the ice coring action at the other end of the assembly. There is a cable termination above that section, and a wireline to the surface. This wireline is guided over sheaves at the surface and onward to a winch. In general, this describes every deep ice core drill. The details of the various internal components give each drill it own unique operating capacities and weaknesses.

Each bottom hole assembly (BHA) is lowered into the borehole until it touches bottom. The drill motor is engaged and cores varying lengths of ice (eg., 6 m in the 5.2”; 3 m in the EPICA) in a good run. The chips are continuously collected by the fluid pumping system, and strained from the fluid in the screen section. When the coring has filled the core chamber, or the chip chamber, is full, the core is broken by tension pulled on the wireline. Small wedges, core dogs, are forced into the core, fracturing the core and releasing it from the ice sheet. The BHA is raised to the surface where, using varying techniques, it is rotated from the vertical to the horizontal position. The screens are cleaned out and the BHA is reassembled and lowered back into the borehole to start the process over. Once again, the details of how this is accomplished differ among the various drill systems.

OTHER DRILLING METHODS

Drilling methods other than a tethered drill system were discussed and eliminated. The following is from the earlier report, *United States Deep Ice Coring Rig Assessment*, and is repeated for the convenience of the reader:

“Mechanical coring rigs that use jointed pipe or coiled tubing are very popular around the various drilling industries. Jointed pipe rigs use pipe that is screwed together, usually in 30-foot sections called joints, to connect the equipment at the bottom of the borehole back to the surface. A continuous conduit is formed allowing for circulation of fluid back to the surface. Coiled tubing rigs are similar except that the pipe is in a continuous coil at the surface and is unreeled and reeled as needed.

The infrastructure for the construction and maintenance and operational knowledge for mechanical coring rigs is vast. The vast majority of the drilling rigs used in the petroleum, mining, environmental, and geothermal industries are of this mechanical style of rig.

However, these rigs tend to be very heavy and require a large logistical load to move and support. These rigs easily weigh in total over a quarter million pounds. They also require more power to not only lift any cores and bottom hole assemblies out of the borehole; they must also lift the pipe or coil. They also require more equipment for the circulation system. This consists of a large pump, with its power needs, pits, and solids separation systems. The average power requirements for a rig capable of using jointed pipe for a 3,800 meter depth rating would be a 1,500 hp for the drawworks (winch), 300 hp for the rotary system, and 1,200 hp for a pump, of which there are usually two, for a total of 4,200 hp. The fuel logistics for this type of rig would be prohibitive alone.

Coiled tubing mechanical rigs would be more efficient from a weight and power requirement. An equivalent coiled tubing rig to the one listed in the previous paragraph would weigh about 80% less. The power requirement is less, approximately 400 hp for a typical 3,000 meter 2 inch diameter coiled tubing rig. This power requirement does not include any hydraulics power needs for pumping. The coil is subject to fatigue every time it is cycled through any bending. This means that for every trip, some portion of the life of the coil is subtracted. Between 100 and 200 trips is the usual lifetime of a coil, depending upon the axial and pressure loading on the coil.

In addition, both of these rigs tend to be less efficient under conditions requiring many trips in and out of the borehole, such as continuous coring operations. In fact, the tripping issue is the one most operators try to avoid as it is labor and time intensive and can be a safety hazard as equipment is moved around.

Thermal rigs are popular for making ice boreholes. However, these types of rigs have a high power demand. According to Mellor and Sellman (1974), thermal drills require two to three orders of magnitude more power for penetrating a unit volume of rock than a mechanical rig. They weigh less than a jointed or coiled tubing rig.

The Cal Tech hot water drill system is ideally suited for rapidly reaching specific depths and examining ice fabric and possible site suitability. This drill is well proven and readily available. It is well developed and has several successful field seasons to its credit. It is easy to deploy and can offer preliminary results that could prevent drilling in an unsuitable location. However, the thermal process can damage the scientific quality of the ice core. It has been noted that the ice core may fracture because of thermal stresses. (Kelley *et al*., 1994) In addition, any debris in the ice causes the penetration rate many of the thermal coring rigs to plummet if not stop outright. Also, thermal rigs cannot core rock.”

EPICA DRILL

HISTORY OF THE EPICA DRILL

The EPICA drill is a descendent from the previous European drills. The EPICA drill's ancestors are the ISTUK design, described in the report, *United States Deep Ice Coring Rig Assessment,* and the Japanese Drill, JARE. Even those drills were derived from an earlier drill, the SIPRE design (Årnason 1974).

The EPICA drill was first used to core to approximately 3,000 meters at NGRIP in Greenland in 1999 and 2000, is being used to complete coring at Dome C this year, and is also employed at DML in Antarctica. The EPICA drill has produced good core to depths of approximately 3,000 meters with the drill's limited ability to core "warm" ice limiting the depth. A drill head of new design was fabricated for use at Dome C this season to allow coring through the warm ice; however, this design did not work as envisaged.

This EPICA design was first used at North GRIP in 1999. A short version of the drill had a test season in 1995 at Hans Tausen in Greenland. The next year, it was tested at Camp Century in Greenland. Another EPICA unit was sent to Dome C the next year. However, this unit was modified to handle the colder temperatures and to incorporate design changes dictated by problems uncovered in previous tests. (Gundestrup, 1994)

In 1997, the EPICA was first used at Dome C. The drill made 216.5 m the first season of use. The drill was briefly stuck at the end of the season but was subsequently retrieved. The next season, it progressed 419.5 m before it got stuck --- this time, permanently---- at 783 m. The drill was abandoned and a new hole started for the 1990 – 2000 seaso. In the following season 1,324.6 m of core was produced and, in the second year, a further 1,413.6 m.

This season (2002 / 2003), before Bill Mason left Dome C, the drill had made 133.6 m in "warm ice" and was at a depth of 3,126.6 m.

The Dome C version of the EPICA drill has new. The Dome C team consisted of personnel primarily from Italy and France with Bill Mason of ICDS participating as a driller for most of the 2002-03 season. The performance of the drill at Dome C is shown in **Table 2** below.

Table 2: EPICA Performance at Dome C

EPICA @ Dome C Season		Start meters	Finish meters	Core Length meters	Days Coring days	Average Rate meters/day
1996	1997	0	107	107	Setting Casing	
1997	1998	107	363.5	256.5	25	10.3
1998	1999	363.5	783	419.5	21	20.0
1999	2000	0	133.6	133.6	Setting Casing	
2000	2001	133.6	1458.19	1324.59	55	24.1
2001	2002	1458.19	2871.74	1413.55	?	?
2002	2003	2871.74	3126.57	254.83	31	8.2

The drill at Dome C has had its share of problems. Augustin and Antonelli (2002) is an excellent source of details on the problems, and solutions, the European team has encountered. They are to be commended for their perseverance. The depth vs.days chart is

reproduced here to show some of the problems encountered. (see **Figure 1)**

The EPICA drill has cored to approximately 1500 meters at Kohnen Station, Dronning Maud Land (DML), East Antarctica. Following establishment of the logistics infrastructure at the German summer station, Kohnen, in 1999-2001 the DML drilling project began in 2001 / 2002 with the drilling and reaming of the pilot hole and placement of the casing. The DML EPICA drill was essentially the NGRIP version, with the older Danish electronics.

1999 NGRIP season 1751.5 m cored (220 m/wk average).

2000 NGRIP season 1,189 m cored (reached bedrock) (145 m/week average).

Specific Drilling performance is as follows:

- At DML the actual, average rate of *drilling* is 30 minutes per 3 meter core length---0.1 meters per minute----at DML the maximum attainable *production rate* is 3 meters per hour of rig time when operating in the 1000 to 1500 meter depth range—this includes tripping and surface handling.
- Tripping into Hole: 1.2 -1.3 m/sec with maximum safe rate of 1.3 m/sec
- Tripping out of Hole: 1.2 – 1.3 m/sec with maximum of 1.3 m/sec (this corresponds to about 20% of the breaking strength of the cable)
- Turnaround Time: ~10 minutes and, at times, less.
- Core Quality is excellent

EPICA DESIGN BASICS

The drill system was designed to be simple and light. With the exception of the winch, two people can carry each disassembled component of the drill.

Drilling fluid consists of a D-60 deodorized petroleum solvent with chlorofluorocarbon densifier. About 50% more fluid than expected was used during drilling at Dome C this season. The densifier tends to cling to the chips causing the chips to sink; this problem has been largely overcome with increased velocity of the drilling fluid at the drill head. The fluid also caused some problems with the lubricant used on the cable when it caused a tar-like substance to form on the cable – this problem has been overcome by working with the cable manufacturer on the lubricant.

The EPICA drill offers many attractive features. Foremost is its minimal drill handling equipment requirement. It utilizes a simple tipping tower to handle the drill during drilling operations, core extraction, and maintenance activities. This is possible because of the shorter drill string length. Core extraction, screen cleaning and maintenance duties are straightforward. The crew number is small which has an effect on overall camp logistics as well as drilling operations. It has a proven track record for its ability to produce science-quality cores.

FEATURES OF THE EPCA DRILL

The following are the major features of the EPICA drill:

- Bottom Hole Assembly (BHA) Weight: 197 kg

- BHA Length: 11 meters
- Outer Core Barrel Diameter: 118 mm OD and 113 mm ID
- Inner Core Barrel Diameter: 104mm OD and 100 mm ID
- Core Barrel Length, overall: 3.5 meters
- Usual maximum core length: 3 meters
- Core Diameter: 98 mm
- Bore Hole Diameter: 129.6 mm
- Pump Rate: 0.5 l/second
- Drill Power Requirement: 400 to 600 W (for BHA)
- Normal Drill Rotation Speed: 63.5 rpm (varies from 50 to 75 rpm)
- Motor drives both pump and drill-head, with 2 fluid pumping strokes of the pump per revolution of drill
- Rotating inner barrel
- 1 mm clearance between core and inner core barrel.
- 9 mm difference between inner and outer core barrel diameter (4.5 mm annulus).
- 2.5 to 3.5 mm pitch on cutter geometry. (9 mm pitch was used on ISTUK drill.)
- Pump diameter is 110 mm.
- A valve plate is used to prevent the loss of chips while tripping to the surface.
- A bayonet style coupling allows a stuck core barrel to be released if necessary.
- A new style filter arrangement was used utilizing a rotating inner filter screen.
- No sleeve used in brittle zone.
- 1 m/s tripping out of the hole (maximum 2 m/s).
- Open valves for 1 m/s tripping into the hole (maximum 3 m/s).
- Radius cutters blades are not used.
- The drill has a cable jar at the connection to the wireline.
- Inner core barrel has no auger flights, instead has linear grooves parallel to rotational axis
- BHA has instrumentation for weight-on-bit (WOB), pressure (behind seals), external temperature, and anti-torque slipping.

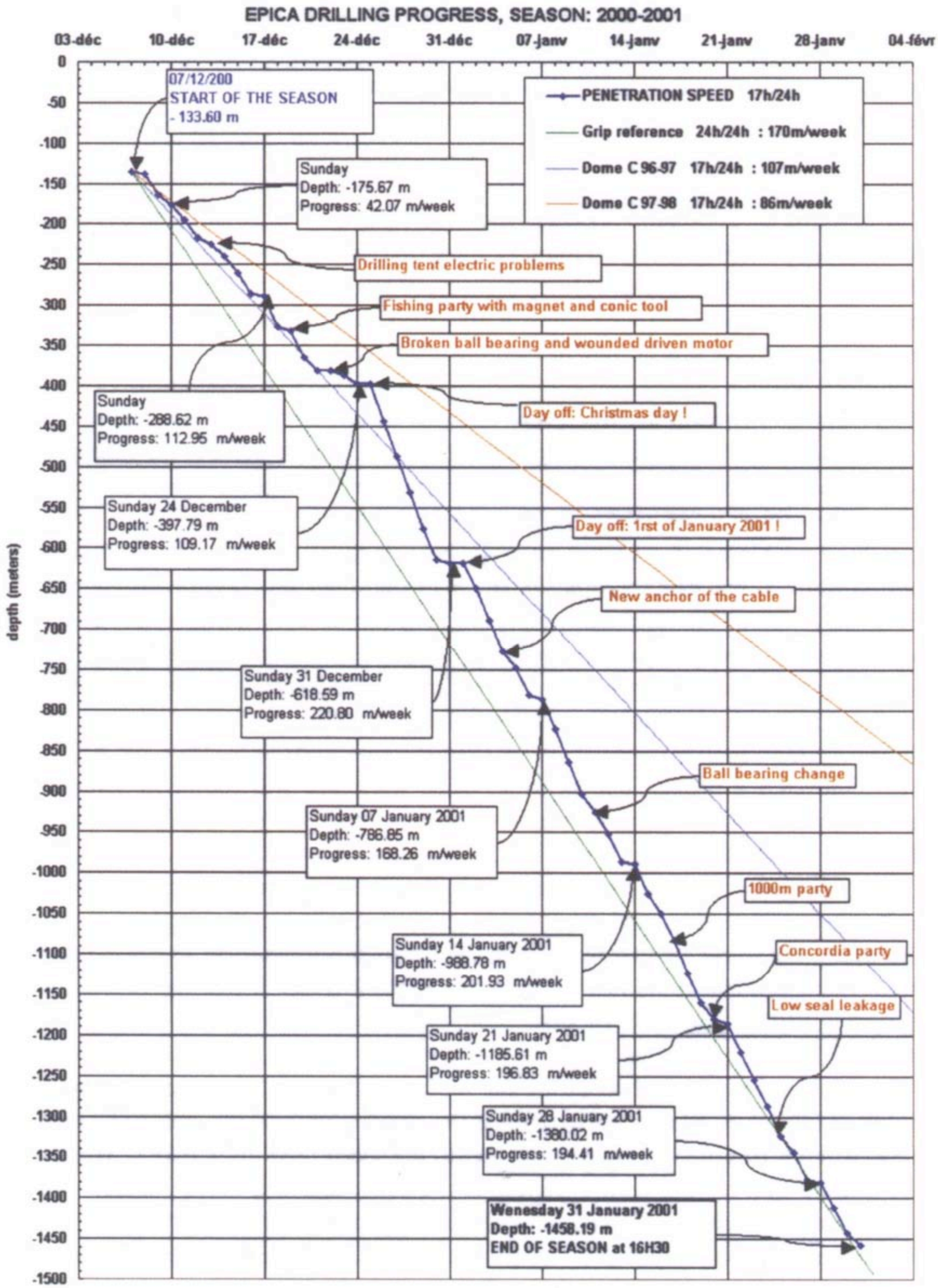


Figure 1 Depth-days chart at Dome C—Augustin and Antonelli (2002)

DESCRIPTION OF EPICA DRILL

The EPICA Drill is a wireline drill system consisting of several subsystems:

- **Bottom-Hole Assembly (BHA)** – The BHA of the EPICA drill consists of the drill cable termination, anti-torque, an instrumentation section, a screen-and-pump section, an outer barrel, an inner barrel, and a cutter head

- **Cable** – A cable consisting of galvanized IPS steel armor and co-axial conductors is used to support the BHA in the hole and to provide a conduit for data transmission between the BHA and the surface control system

- **Drilling Fluid Handling System** – This system consists of the drilling fluid itself, a screen-and-pump cleaning system, and a fluid recovery system. The drilling fluid used by the Europeans consists of two components: a deodorized petroleum solvent (D-40 at DML and D-30 at Dome C) with a chlorofluorocarbon densifier. It performs the dual functions of drilling media (to suspend and transport chips) and to provide the hydrostatic pressure to keep the borehole open indefinitely. Without this hydrostatic compensation function, it would be impossible to drill in a "dry" hole to depths greater than about 350 meters.

- **Surface Drill Equipment** – The surface drill equipment consists the draw works – a winch capable of holding 4000 meters of cable -- and a 13-meter-long tilting tower with maximum on-axis loading of 80,000 N (18,000 lb-f). :

- **Dome-C Winch Drive System** – A control console with two Variacs is used to control the winch speed and direction. Two computers are used to pilot the drill and to acquire data from the drill and surface equipment instrumentation.

- **DML Winch Drive**- a EUROTHERM variable frequency controller driving a Brook-Crompton 480 VAC (50 Hz) , 3-phase induction motor via a SEW-brand spiral-bevel-gear reducer, implementing digital encoder feedback. The encoder feedback allows particularly fine control of speed during drilling advance; the system actually has provision for computerized feedback and control via a PC computer and RS-488/232 interface but, in fact, the present system is minimalist and relies upon operator intervention via a dedicated EUROTHERM keypad. Components for the interface have been purchased but not implemented at this time…this is envisaged for next season, however. The SEW brand gear reducer drives the LEBUS-built winch system for hauling speeds of about 1.3 m/sec. Maximum descent speed is essentially fixed (governed by drill geometry and weight), and typically averages about 1.25 m/sec. Speeds through the casing are operator-limited to 0.6 m/sec to limit damage to the casing, drill, and core as there is frequently reduced levels of fluid here and the casing may in fact be "dry." The winch incorporates a failsafe disc-brake system, spring-activated and requiring electrical power to release it. In the even of power failure to the winch-drive system (through which the brake is connected), the brake is automatically engaged and remains in this state until power is restored and winch operations are manually re-set. The brake system is capable of dynamically braking the drill system (BHA, cable, winch drum, sheaves, etc.), even if engaged at a full-speed runaway.

- **DML Borehole Electronics-** we implemented two borehole control electronics. **(1)** The first, and oldest, of these is a hand-me-down from the ISTUK drill system and is approximately 20 years old. Its purpose-built computer is obsolete and implements wire-wrap technology that is sensitive to moisture and other contaminants (there is, for example, no conformal coating applied anywhere). The sensor package for tilt relies upon Japanese swing-pendulum potentiometers that date to ISTUK. The power-handling components have been renovated, as EPICA no longer relies on NiCd battery storage as in the ISTUK drill. EPICA uses DC-DC voltage converter modules to convert ~400 VDC from the wireline cable down to about 11 Amperes at ~50 volts as used by the drilling motor. DC-DC modules capable of lower currents are used to supply voltages suitable for operating the instrumentation (temperature, pressure, tilt sensors), computer, and analog-digital converters. **(2)** During the 2002-2003 season we implemented a new borehole computer system based on a commercially available module. This required new communication software on the surface. This module offers faster computation speed and the capability of handling more inputs and—beyond the initial teething period--- proved to be a greatly appreciated and reliable improvement.

- **Core Extraction Equipment** – The tilting tower is rotated to a horizontal position for core removal. The core barrel is extracted from the BHA using a hand operated or motorized winch; once extracted it is on a "retrieval table," and out of the way of the BHA. While on the table, the core can be extracted and the screen and pump cleaned of ice chips. Meanwhile, a previously cleaned and prepared core barrel is reinserted in the BHA so that the drill can be returned to the vertical position and drilling resumed.

- **Trench and Casing** – The drill trench (that is, the slot in the floor below the tower) allows the rotation of the tilting tower from the vertical to the horizontal position. The drill borehole is cased from the bottom of the trench to below the firn-ice transition with 25.5 cm-OD fiberglass-reinforced irrigation pipe. The hole is covered, except during removal of the BHA, with a slotted cover to prevent foreign objects from entering the hole.

- **Ventilation System** – Fans in the drill trench, at the cleaning station, and in the fluid treatment system are used to prevent the accumulation of heavier-than-air drill fluid vapors in the working area.

Each of these subsystems is more fully described in the following section.

EPICA BOTTOM HOLE ASSEMBLY (BHA)

Drill Cable Termination – A galvanized IPS armored cable is terminated on the free-rotating side of a thrust bearing. This termination is the strength connection to the BHA. The cable conductors are connected to a hollow brass cylindrical conductor fixed and electrically isolated on the same side of the thrust bearing. The thrust bearing provides a means for the BHA to rotate freely on the cable without twisting it.

Cutter Load Measurement - The fixed side of the thrust bearing is attached to the underside of a cylindrical, stainless steel weight. The full weight of the drill acts downward through a coil spring, compressing it, on top of the cylindrical weight. The cylindrical weight is guided on two long shafts attached to the top cap of the instrument section on the BHA. A linear displacement transducer housed in the top cap of the instrument section is used to measure the position of the cylindrical weight. As the load in the BHA increases, the coil spring on top of the cylindrical weight is compressed more. As the load on the BHA decreases, the coil spring is compressed less. Thus, a relative motion is seen between the cylindrical weight and the top cap of the instrumentation section of the BHA. The linear displacement transducer is calibrated to indicate cutter load as a function of the position of the cylindrical weight.

Mechanical Jar - The cylindrical weight referred to above is commonly called "the Hammer," and coil spring provides a means of storing energy as the core is in the process of being broken by the core dogs. To aid in core breaks, the draw works pulls on the cable and the cylindrical weight moves upward against the coil spring compressing it until the cylindrical weight hits hard, stops -- producing the desired shock.

Sliding Electrical Contacts - Two sets of spring-loaded electrical contacts ride upon the hollow cylindrical conductor. The hollow, cylindrical brass conductor is free to move up, down, and rotate in the contacts without interrupting their electrical connection. One contact is for power and the other is for instrumentation. The body of each contact is attached to a plate clamped to the three long shafts guiding the cylindrical weight. Wires from these sliding contacts enter the pressure-tight instrumentation section via a Sea-Con style connector.

Anti-torque - Three anti-torque spring leaves are symmetrically mounted around the outside of the hammer section.

Instrument Section - The BHA instrumentation is protected inside a pressure-tight housing. From top-to-bottom, the upper end of this section contains the drill's power-conversion electronics, on board computer, instrumentation electronics, and motor-drive electronics; this is followed by the PMDC motor, directly coupled Harmonic Drive gear-reducer, output drive-shaft, and high pressure rotary seals in the lower end. The following drilling information is transmitted to the surface from the BHA instruments:

- Cutter load (N)
- Motor current (amps)
- Motor voltage (volts)
- Motor speed (rpm)
- X-Inclination (degrees)
- Y-Inclination (degrees)
- Diff-Inclination (degrees)
- Total Inclination (degrees)
- Upper seal pressure (kPa)
- Lower seal pressure (kPa)
- Motor shaft seal pressure (kPa)
- Motor drive electronics temperature (degrees C)
- CPU temperature (degrees C)
- Gear reducer temperature (degrees C)
- Motor temperature (degrees C)

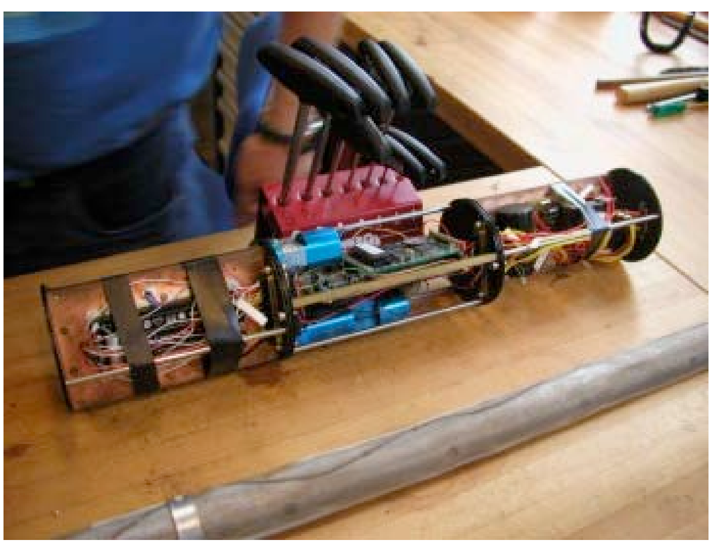


Figure EPICA Electronics Package and Screen

Outer barrel - The outer barrel of the BHA attaches to the lower end of the instrumentation section. Drilling fluid flows from the inside of the filter section to the outside of the drill's outer barrel via large holes at its uppermost end.

Figure 3: Bottom of EPICA Pump

Screen Section and Pump - A rotary-valve (shutter plate) on top of the screen-section is manually opened to allow drilling fluid to bypass the screen when tripping into the hole. This shutter plate closes once the drill motor is turned on, forcing the drilling fluid to flow through the screen. At the lower end of the hollow drive shaft is the reciprocating pump. The screen-covered hollow drive shaft is attached to the cam followers (rollers) that drive the two-lobed cams (upper and lower), causing the reciprocating motion of the pump. The body of the pump is keyed to the outer barrel upon assembly, preventing the cams from rotating when acted upon by the cam-followers. (See **Figures 3** and **4**)

Figure 4: EPICA Pump

Another rotary-valve (shutter plate) is located just on top of the pump. Its is manually opened for tripping the drill into the hole and closes when the drill motor is turned on. At DML, this feature was entirely removed without ill effect. The screen drive shaft is attached to the rotating side of the pump. Another rotary valve plate is located just on top of the pump. It to is manually opened for tripping the drill into the hole and closes when the drill motor is turned on. The fixed side of the pump is keyed to the outer barrel to prevent it from rotating.

Core barrel - The core barrel attaches to the lower end of the rotating part of the pump assembly by a quick-release bayonet-style mount on the so-called SuperBanger. The SuperBanger can be used to provide a dramatic, upward "hammer blow" directly to the inner barrel. The shock of this blow is far greater than can be had from the traditional "hammer."

Figure 5: Coring Head with Ice Core

The SuperBanger also incorporates another useful feature: by reversing the direction of the drill it is possible to release a bayonet-type mount and leave the inner core barrel in the hole while retrieving the rest of the drill. Drillers on the EPICA program have devised a method to retrieve the core barrel in the event it can be freed; the latter generally involves the application of glycol.

Like most electromechanical drills of this genre, the rotating inner core barrel has auger “flights” (spirals) around its outside diameter. These have approximately a 45-degree spiral and are arranged in a triple helix--- one flight per cutter tooth.

The EPICA core barrel has full-thickness polyethylene flights attached for about 15 cm near the top and bottom of the core barrel to centralize it within the outer barrel. Throughout the middle section of the core barrel, aluminum half-thickness auger flights minimize friction between the barrels. These act to stir the (chips + fluid) mixture within the annular space between the inner and outer barrels, preventing clogging. The degree to which the flights promote fluid motion is unknown and debatable, but that they prevent clogging is undeniable.

Cutter head - The cutter head is attached to the core barrel by three flush-mounted buttons, with eccentric, stepped diameters. Contrary to popular belief, the eccentricity is more a matter of accommodating small errors / variations in machining rather than providing a positive method of “drawing tight” the cutter head. See Figure 5.

The cutter head has three cutters and shoes. The diameter of the core produced with this head is approximately 97.6mm.

EPICA Surface Equipment

Surface equipment requirements for the EPICA drill are one of its attractive features. The entire drill string is handled on a tipping tower that swings down into a below grade pit. This makes for very easy maintenance and operation. The pit is relatively easy to prepare and requires only a small amount of servicing. All mechanical structures are at floor level and can be easily accessed. One drawback of this system is the confined space area created by the pit. The vapor density of n-butyl acetate is 4 (air is 1) and would cause the butyl vapors to sink into and settle in the pit, causing a potentially hazardous work environment in the pit.

Draw works - The winch has the capacity to hold 4000 meters of cable and was manufactured by Lebus in the United Kingdom. It uses a 3-phase, 15kW motor and has a speed range of 0 to 1.4m/s fully loaded. The winch has a grooved drum and a mechanical level wind for trouble-free spooling. The weight of the winch is approximately 2 tons. A detailed description was previously given.

Tilting tower - The tilting tower was designed at the University of Bern, Switzerland. It is approximately 13 meters in length and designed for a maximum 80,000N (18 000 lb-f) load applied at the crown sheave. The tower pivots at its base and it actuated by an linear motor drive. In its horizontal position, it cradles the drill at a comfortable working height. The crown sheave on top is instrumented for cable tension and the lower sheave (this is the one which changes the cable direction toward the winch) is instrumented for cable length and speed.

Retrieval table and Chip Handling - The retrieval table is constructed of a stainless steel trough with a set of rails and cradle blocks to accept the full core barrel as it is extracted from the BHA. A second set of linear guides, adjacent to the first set of rails, are used to hold the screen and pump assembly for cleaning. A motorized winch is used to assist in extracting the core barrel and screen and pump assembly from the BHA. The retrieval table is mounted on a set of linear rails so that it can be moved into position to accept the core barrel, then moved to accept the screen and pump assembly, and finally moved out of the way of the BHA so that a clean screen and pump assembly can be reinserted along with a clean core barrel and drilling resumed. Once out of the way of the BHA, the retrieval table is positioned to extract the core and clean the screen and pump assembly.

Chip handling - As the screen-and-pump assembly is extracted from the drill, fluid and chips drain and fall into a pan floored with a fine-mesh wire-screen cloth. The drilling fluid drains through the wire cloth into a larger tank below. The tank supports the chip pan with the chips and is on casters for easy movement to the centrifuge station. There, the drained chips are manually scooped out and placed into canvas sacks and transferred to the centrifuge for final fluid extraction.

Figure 6: Drill Trench at Dome C

Centrifugation takes 10 to 30 minutes depending upon the degree of extraction required. The vast majority of the fluid is extracted within a couple of minutes. The centrifuged chips are then removed from the centrifuge, dumped from the bags, weighed, and discarded

Control System-As previously noted there is considerable variation in the control systems, which are summarized here:

At Dome-C, the control console for the winch has two Variacs, one for high-speed winch control and the other for precise slow-speed winch control when drilling the core. A separate direction switch, brake switch, emergency stop button, and electrical meters are also contained in the console. A computer is used to control drill functions and for acquisition of drill parameters while drilling. A color printer is used to print the computer screen for documentation after each drill run. A secondary display -- showing cable load, cable load maximum, depth, and speed --- is used as a back-up in case the primary computer fails.

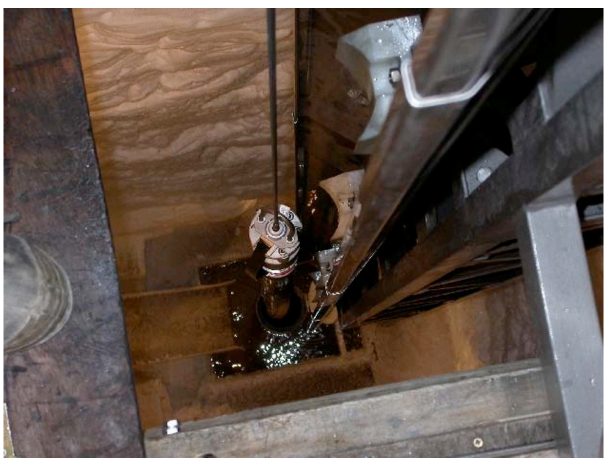


Figure 7: Drill Trench and Borehole at Dome C

At DML (and NGRIP) the winch is controlled by a EUROTHERM variable-frequency drive, and is capable of extremely fine and reproducible motion via feedback from a digital encoder mounted on the motor itself. The parameters required to control the winch are entered through a dedicated EUROTHERM digital key-pad, but components are already in place for computerized interface with feedback control. Once computer control is implemented, it will be possible to drive the winch through the computer with ramp-up and ramp-downs at appropriate depth intervals and automatic approach to the drilling depth.

Also at DML, the surface equipment for controlling the drill consists of a PC type computer, a MODEM for communicating with the down-hole electronics (over the same wires which carry the 400 VDC drilling power), a bubble-jet printer for recording data, and a Siemens strip-chart recorder for logging drill-motor electrical current.

Drilling trench - A well-lighted 6.5-meter-deep trench allows rotation of the tower into its vertical position. One end of the trench is inclined with steps for accessibility to the hole (see **Figures 6** and **7)**. A drip pan is used at the bottom and extends up along the inclined wall of the trench to collect drippings from the drill as it rotates with the tower. A large duct was excavated into one side of the trench to remove vapor generated in the trench and that sinks there due to its density. That is to say, it acts as a vapor sump.

Chip handling - As the screen and pump assembly is extracted from the drill, fluid and chips fall into a container with a fine screen cloth on its bottom and the drilling fluid filters through into a small rectangular tank. The chips stay in the container with the screen. The rectangular tank supports the container with the chips and is on casters for easy movement over to the centrifuge.

Drilling Fluid – The drilling fluid used by the Europeans is a two-part fluid consisting of a highly refined, deodorized petroleum solvent (D-40 or D-30) and a chlorofluorocarbon densifier (HCFC-141b). The densifier is being phased out and will be replaced on the world market with a product (HFC-365) having lower ODP (Ozone Depletion Potential) within the next two years or so. Whether HCFC-141b or its new replacement will be allowed for use by the US program in Antarctica remains to be seen.

Drilling fluid handling system – Upon extraction from the drill, the fluid-laden chips are drained, and then centrifuged to remove as much of the drilling fluid as possible. The dried chips are then weighed and discarded. The weight of dry chips is recorded for each run along with the core length, diameter, and cutter pitch. A running log is kept to monitor the amount of chips lost and remaining in the hole, as chip accumulation could contribute to the sticking of a drill.

Fluid from the chips, cleaning station, and drip pans under the tower and winch is periodically pumped into a 350-liter holding tank. When the fluid level in the hole has dropped after several coring runs, new drilling fluid mixture is prepared in the holding tank. Petroleum solvent D30 (or D40) and HCFC-141b is added to the tank in approximately correct proportions. The mixture is stirred with a motorized paint mixer. The temperature and specific gravity are then measured, and corrective amounts of D30 (or D40) or HCFC-141b are added and the mixture stirred again until the temperature-corrected specific gravity is attained. The contents of the tank are then pumped into the borehole through a meter which measures the volume of the mixture added to the hole and also keeps a running total of the volume of all the fluid which has been added.

Ventilation system - The fumes from the drilling liquid are heavier than air, and this fact influences the design of the ventilation system. A large ventilator fan draws air from the bottom of the drill trench and exhausts it outside the drill tent. Two smaller ventilator fans, one located at floor level near the fluid treatment system and the other located at floor level near the screen-and-pump-assembly cleaning station, exhaust air to the outside of the drill tent. The total volume of air exhausted is around 250 cfm.

According to Frank Wilhelms, at DML the ventilation capacity is sufficient to completely exhaust the entire drilling trench every 5 minutes. This amounts to 5000 cfm or about 144 cubic meters per minute.

Clothing/safety equipment -Lined rubber gloves are used for all drill and fluid handling operations. The gloves are kept warm (and dry) in a heated box easily accessible near the drillers' cabin. At Dome C, the cleaning station operator dons a transparent face-shield to prevent s drilling fluid from splashing into the face and eyes.

Hole casing - The casing is a glass-fiber-reinforced plastic pipe extending from the bottom of the drilling trench to below the firn-ice transition. The top-end of the casing is usually covered by a hinged door. The door can be operated remotely, from the drill-trench floor. The only time the lid is opened is to allow the drill to pass into or out of the casing.

DRILLING OPERATION WITH EPICA

Initial activities before production-coring begins includes establishing the camp, digging the drill trench, drilling the pilot hole, setting the casing through the firn, and setting-up the drill. The casing is set from the bottom of the drilling trench to below the firn-ice transition (approximately 100 meters) after a 143 mm diameter pilot hole is drilled and then reamed to 25.5 cm. The casing is glass-fiber-reinforced plastic pipe with gasketed, liquid tight joints. Once the tilting tower is in place over the drill trench, coring can begin.

The normal sequence of events during one complete trip of the drill is as follows:

1. The drill is lowered to the bottom of the hole and the depth verified. Valves on the pump are typically opened to allow faster tripping into the hole.

2. Coring begins with the driller monitoring tension on the drill, electrical load, depth …

3. Once drilling has filled the core barrel, the drill is tripped out of the hole using the draw works. The speed of the winch is slowed as the BHA approaches the surface

4. Once the BHA is correctly positioned along the tilting tower, the tower is rotated from the vertical to the horizontal position.

5. The core barrel, which contains the core as well as the screen and pump section of the drill, is unlocked and extracted from the BHA onto the retrieval table using a motorized winch.

6. Core barrel and hollow-shaft sections are decoupled from each other;

7. The core is extracted from the core barrel, the filter screen and pump is cleaned by scraping away loose chips using a gloved hand, and flushing with drilling fluid supplied by a pump and garden-hose arrangement.

8. The hollow shaft, now clean, is reinserted into the BHA

9. The “clean” core barrel is coupled to the SuperBanger (bottom end of hollow shaft) and the entire assembly is inserted into the BHA.

10. Once all connections are made and checked, the tilting tower is moved back to the vertical position and the drill is ready to begin the next trip.

11. Fluid is recovered form drip pans and from the chips.

The availability of spares for the core barrel and hollow-shaft assembly can make off-line cleaning of these components a reality but this does not add materially to the production rate. A possible exception would be at shallow depths when surface-handling time would be a substantial component of the total time spent.

OBSERVATIONS CONCERNING EPICA DRILL

Bill Mason and Michael Gerasimoff of ICDS participated in the 2002-03 field seasons at Dome C and Kohnen Station (DML), respectively. Based on their experiences, as well as conversations between members of the development team and European drillers and engineers on site and at meetings in Denmark and Germany, the following observations are made concerning the EPICA drill.

- **Portability** – The drill system is light and easy to handle. However, some of the weight and handling characteristics of the drill are due to the maximum core length of 3.5 meters. This results in lower production rates than might be achieved with a longer core barrel.

- **Drilling Fluid** -- The handling and mixing of the drilling fluid was not an issue at either Dome C or at DML. The D30/D40 and HCFC-141b mixtures were easy to prepare and use. Handling required only protective gloves in the well-ventilated drill tent without the requirement of a respirator and other safety clothing or devices. The availability of HCFC-141b for use in the US program, however, is in question. HCFC-141b may or may not be phased out of production and may or may not be available under US guidelines in either continental US or under more restrictive guidelines imposed for Antarctic operations. However, a HCFC-141b alternative is being developed, HFC-365, and this has lower ozone depletion potential (ODP) and is expected to replace HCFC 141b in most applications sometime in the next year or two.

Fluid Problems - Rumor abounds that the densifier has a tendency to "separate from the solvent" and "coat the chips." This suggests two possibly unrelated problems: 1) simple mechanical un-mixing of the two phases, and 2) preferential adsorption on ice surfaces.

1) Un-mixing: Generally, the first does NOT appear to be a problem and fluid at rest in the borehole does not undergo wholesale separation. The adsorption onto the chips appears to be due to the slightly polar nature of the HCFC molecule, which then attaches to the polar ice molecule (No puns are intended here!). Of course the greater the surface area (fine chips vs. borehole walls) the greater the effect of adsorption. The reduced density of the borehole fluid has been implicated--- probably incorrectly--- in an under-compensated situation down-hole and sticking of the drill. This is probably a rash statement as the conditions of most drill-sticking are never really known. Given fully and accurately instrumented BHA, under-compensation should never be a problem because tank-car additions of densifier can be added where and when required.

2) Chip Coating/Clogging: That the coating of the chips has also caused the filter assembly to clog and make chip retention problematic is also a reckless statement. Clogging of the filters with chips was NEVER noted at DML , nor at Dome-C. If clogging has actually existed in the past, it more likely results from additions of hydrophilic ethanol and glycol. At DML we were using less than 5% of the industrial ethanol employed by the Danes (at their Greenland drilling operations), only when and where absolutely necessary!

- **Brittle Zone Cores** – The EPICA drill has demonstrated the ability to recover full-length (3.5 meter) good cores in the brittle zone.

- **Warm Ice** – The EPICA drill does have problems in warm ice. At Dome C recovery rates declined appreciably in the warm ice. A new cutter design was tried but did not prove to be successful. Injecting glycol from a "tank-car" in the BHA appeared to improve coring in warm ice.

- **Drill Electronics** -- The drill electronics package will require a major design commitment. Specific details are not known, just that many of the electrical components are not currently available. The drill-to-surface communication speed is relatively slow compared to what is desirable in a state-of-the-art drill.

- **Mechanical Reliability** – Reliability of the pump and mechanical drive seem to be excellent.

- **Cutter Pitch Sensitivity** The EPICA drill is sensitive to variations in cutter-to-shoe clearance variations, particularly in warm ice conditions. It is possible to accurately set, and maintain indefinitely, the clearance by using the proper protocol.

- **Winch** – The Lebus-built winch mechanical and level-wind mechanism worked flawlessly.

- **Dome-C Winch Drive:** At Dome C the drive had a tendency to "fault" resulting in free wheel, dropping the BHA until the operator could react and manually engage the brake or hit the emergency-stop button. This winch fault was observed to happen at random intervals, at any time of day, and was not dependent on direction or speed of winch operation. This worst-case scenario happened to this operator (Bill Mason) on one occasion when the drill was within a meter of the bottom of the hole. The winch failed, and with the weight of the drill and almost 3,000 meters of cable in the hole and no time to react, dropped the drill. Upon impact with the bottom of the hole, the drill-to-surface electrical communication was interrupted and the run was lost. The upside of this problem is that it kept the operator alert thereafter! There was no obvious solution to this problem. The winch motor control manufacturer had not been able to find the problem and the problem remains unresolved.

- **DML and elsewhere**: The winch drive system at DML and NGRIP are significantly different and did not have these faulting problems. See previous notes**.**

- **Tilting Tower** -- The tilting tower also worked well. However, the linear motor drive that controls the tilting has been a problem from the outset. Initial designs were underpowered for the load applied and resulted in one accident wherein the lead-screw nut stripped out and the tower fell from the horizontal position to the vertical. Luckily, no one was injured. The drive (which resembles a hydraulic cylinder at first glance) is somewhat temperature sensitive and regularly gives headaches at conditions below –30 C. Likewise, the electronics control panel is outsized (about one meter square by 35 cm thick!) and requires insulation and heaters to keep it operational. This drive system is, overall expensive and not required, and could be easily replaced with readily available hydraulic components.

- **Drilling Control System** -- The EPICA drill is run by open-loop manual control for all coring functions. The controls are very sensitive and it is desirable for a state-of-the-art drill to have the capability to run in a closed loop (automatic feedback) mode to optimize its performance and safety.

- **Pump: Flow Rate** – The pump worked reliably and consistently, however, there is not much chance to increase its flow rate without a major design effort. Also, there was no way to be sure that the pump was *really* working or what effect an increase or decrease in drill motor speed had in the pumping rate. Incorporating a flow meter would require another design effort. There is no obvious solution if a flow meter is desired. There were concerns by the Dome C crew that the pump did not sustain enough flow for the warm ice conditions this season. The pump is not a positive displacement pump despite the fact that it is a piston type design; this emerges because as the maximum pressure applied to the piston and hence the fluid is limited by spring pressure. Once a blockage forms and pressure builds to the maximum level one of two things happens: 1) the blockage is moved and flow resumes, or 2) the blockage persists and fluid flow slows or stops completely.

- **Personnel** – Operation of the drill requires highly experienced, trained drillers. Many of the drillers at Dome C were involved in the development of their drill and had a good deal of experience in its operation. The crew at DML were also experienced, but were hampered by a system that has components beyond the end of their normal, useful, life.

- **Bed Rock Coring** – There is no rock drilling capacity nor is it readily adaptable to rock coring activities. The available power down hole could be a limitation to rate of penetration but, given that the amount of rock to be drilled is very modest, this might not be an issue. Stated another way, the drill's torque is more than adequate to turn a BQ or even larger diamond coring bit, but the rate of penetration might not be stellar. Breaking core and recovering it would likely require separate tools such as a slide-hammer arrangement and this is probably going to be the case with the DISC drill as well. It would be well to consider making an entirely different sonde for rock coring, incorporating essential features from the ice-coring version such as the communications and controls.

- **Core Quality** – Core quality has been very good. Cores recovered at Dome C appeared to be good even in warm ice. At DML, cores were generally excellent.

- **Deviation Drilling** – The EPICA was not designed for replicate coring. It is uncertain that the drill can be adapted to allow for deviation drilling.

10.0 CM DEEP ICE SHEET CORING DRILL

HISTORY

Since this is a new drill, there is no history. However, its ancestry is rooted in all of the previous drill systems. The 5.2" drill history can be found in the report, **United States Deep Ice Coring Rig Assessment**. That section is repeated here for the convenience of the reader.

A Brief History of the 5.2-inch Deep Ice Core Rig

"The rig was first constructed in 1988 at the University of Alaska, Fairbanks for ice coring and drilling operations for the Greenland Ice Sheet Project for the National Science Foundation (Kelley et. al., 1994).

The rig was first used in Greenland on the GISP2 project from 1989 to 1993. The total depth of the borehole cored was 3,054-m (10,020-ft) including 1.5-m (4.9-ft) of bedrock. Difficulties encountered with mobilization and rig up and initial drill operations basically scuttled the first season. One season was lost because of a wireline failure. The overall quality of the ice core was good outside of the brittle sections of the ice sheet. In the brittle sections, the quality was poorer.

The next time the rig was used, in was in Antarctica at Taylor Dome during the 1993-1994 season. The rig was used to drill 550-m (1,804-ft) of ice. Operations were relatively smooth as many of the drilling crew at GISP2 was onsite at this location, too. The ice core quality in the brittle zone was poor. Spare parts availability and time constraints prevented operations in the bedrock.

The last time the rig was used was in Antarctica at Siple Dome. The rig spent three seasons on the ice. Difficulties turning a new 30-cm (11.8-in) core barrel used to drill the surface borehole required modifications in the field to get the borehole built and surface casing set. The next season, many more difficulties were encountered. For example, the core barrels are bent, the connections don't mate properly, and various parts didn't fit. Overall, a poor season with only 100-m (328-ft) of core recovered. The third season is somewhat better in that 850-m (2,789-ft) of core is drilled. However, the ice core quality is poor to worse with many shattered sections. In addition, drilling fluid was in short supply curtailing some operations. No bedrock is cored.

It is useful to remember that this drill did recover 4,554 m of various quality core. If the Siple Dome experience is discounted, the drill averaged 720 m per season.

Problems

In discussions with many individuals on site at Siple Dome and other users of the 5.2-inch ice core rig, many problems occurred. These included core recovery problems, maintenance difficulties, operational inefficiencies, borehole fluid troubles, and human health and safety problems.

Ice recovery through the brittle ice zone was poor to non-existent. There were mechanical problems with the drill such as bit damage to the core, ice fractures from what appeared to be the core catcher design, and ice core fragmentation.

Trip times in and out of the borehole were slow because of wireline and borehole fluid problems. It was observed that the downhole core system was out of balance. When running while hanging at the surface, the coring system would whirl violently. This could also lead to brittle ice failures as the core barrel whips around downhole.

The borehole fluid, while useful for coring, is difficult to handle and has safety and environmental problems. Also, the fluid level within the borehole varied. Rig crews and core handlers must use constricting safety equipment that hampers motion and leads to rig operating difficulties. The borehole fluid is also hazardous to the environment and difficult to transport.

In interviews with individuals involved in field operations, there were some personnel issues. Some felt that safety issues not given full attention. Others felt that there was friction on site between some of the drilling operators and scientific team.

The mobilization and demobilization of the rig was very complicated and was lengthy in time.

Other problems include a heavy logistics burden and very slow operations. Another major problem was that engineering, logistics, and field management was less than needed for optimum operations."

The Deep Ice Sheet Coring (DISC) drill is a new design proposed by ICDS. Although it is a new design, the general design parameters do not deviate significantly from previous designs. Like every ice core rig built in the recent past, it is a wire-line drill. This type of drill offers so many advantages over other alternative design types that it is the clear choice.

There are a few departures from previous designs.

FEATURES OF THE DISC DRILL

- A rotating outer barrel stabilizes the BHA and allows for improved chip transport because the bit can be designed to force the fluid to flow across the cutters.
- Separate and independent speed controls for the drill motor and the pump lends to a more versatile coring parameter control.
- The separate motors also give the ability to pump the drill into and out of the borehole.
- A non-rotating inner core barrel will facilitate core orientation, allow for mechanisms to sleeve brittle ice cores for improved recovery, and can help reduce stresses in the core from rotational friction.
- Cutter speeds of 60 to 180 rpm are possible.
- The pump is "off-the-shelf", has a large pumping rate, and is pumping clear fluid without chips.
- The BHA is relatively short and yet it will take up to 6 m long cores.
- The design will be more amenable to replicate coring

The present DISC drill concept has been configured to meet the design criteria put forward from the ICWG to ICDS: to drill a minimum 100 mm diameter ice core up to 3,800 m deep in ice of a temperature range –4ºC to –50ºC. The primary focus of this concept was to create a bottom hole assembly (hereafter, the "BHA") that could be evaluated as an alternative to the EPICA design

The weight of the assembled tower is approximately 1,350 kg. The length of the bottom hole assembly is approximately 9 m as configured to drill a 3 m long core, though design is ongoing to increase the core length. Two major assemblies have been created to illustrate and explore one possible configuration for the bottom hole assembly and tilting tower. Each assembly is represented as a virtual solid model. The assemblies are complete to the point where several discussions over the technical issues regarding the function of each will be required before further design effort is expended.

The primary, and largely mechanical, focus of DISC has been configuring the BHA to optimize chip transport. No tests or theoretical analysis have been done to prove the characteristics of its chip transport. The design, as put forward herein, incorporates the experience and suggestions of several individuals, including valuable comparisons to the Russian "Vostok" (KEMS-132) drill. Our proposal is a first pass at what we consider to be a state-of-the-art deep ice core drill.

Considerable time was spent on understanding the drill handling process and the requirements for handling each bottom hole assembly section. Various configurations were examined and analyzed.

The secondary focus was the surface handling of the BHA. A tilting tower assembly was developed along the same concept as the EPICA drill. The design of the EPICA tower can be extended to handle a drill with a 4-meter-long core barrel. Consideration has also been given to moving the pivot to the bottom of the tower, thereby eliminating the need for a deep drilling trench. This is of course at the cost of requiring higher housing above the floor of the drill shelter. A bottom-pivot tower could handle a drill with a 6-meter-long core barrel but this is obviously more physically demanding. Tall, tilt-up towers are used extensively in the wind turbine and oil & gas industry and this is encouraging.

BHA Description

The main parts of the BHA arranged from top down are as follows:

Load cell, hammer, anti-torque, and electrical / instrument section A fluid-pressure-tight “Sea Con” style electrical connector, slip-ring assembly, a mechanical hammer, and wireline termination are located at the upper end of the BHA’s pressure-tight instrumentation housing (the exact configuration of these items is not shown in Figure 1). Another Sea Con style electrical connector for connections onward to the pump and drill motor is located at the lower end of the instrumentation section.

The hammer, sometimes called a wireline “jar,” allows kinetic energy to be rapidly converted to a stress wave. Such a sharp “rap”, is a first line of defense for freeing a stuck drill or to facilitate core “breaks.”

The application of torque from the drive motor to the cutting head, were it not be reacted elsewhere, would simply caused the cutting teeth to bite-in and thereafter the rest of the BHA would spin uselessly in the hole. To supply this torque reaction, a so-called “anti-torque section” is incorporated into every electromechanical type of drill.

In the case of DISC, four anti-torque spring leaves are mounted around the outside of the instrumentation housing. The upper anti-torque spring pivot is held in a fixed mount. The lower anti-torque spring pivot is located in a movable spring mount guided on the outer surface of the instrument section. The lower pivot is prevented from rotating by a key. A coil spring provides preload for the anti-torque spring leaves and the preload is adjustable via a clamping sleeve. The centerline of each spring leaf is offset slightly from the centerline of the instrumentation section, providing better bite in the borehole at a given preload setting. In this way, there will be less sliding friction between the bore’s wall and the anti-torque device. In practice, this will allow the drill to move smoothly at slow drilling speeds.

Consideration is ongoing to incorporate the anti-torque blades into the lower body of the BHA, thereby shortening the BHA further.

The instrumentation section consists of a pressure vessel containing all the power, drive, and control electronics. The electronics in this section will monitor power consumption, cutter speed, BHA- (and, therefore, core-) orientation, anti-torque slippage (spinning of the BHA in the hole), inclination, temperature and pressure at various points inside and outside (the former leading to detection of fluid leakage into the instrumentation pressure vessel), motor vibration, and load on the cutters via a load-cell. As suggested elsewhere, it may be possible to incorporate a system built into this section that could be used to help steer the drill via variable pressure applied to each of the antitorque leaf springs. Such a steering system is obviously an electro-mechanical complication that might be best tackled later, as a refinement to the system.

Figure 8 shows the mechanical configuration of the instrumentation section and anti-torque assembly. The instrument section must have both dynamic and static pressure seals rated to 68 MPa to protect electrical transformers, motor drive electronics, CPU, and sensor (current, voltage, frequency, pressure, temperature, acceleration, etc.) electronics. The following information is transmitted to the surface from the BHA instruments:

Cutter load (N)

Drill Motor Current (A)

Drill Motor Voltage (V)

Drill motor Speed (RPM)

Pump Motor Current (A)

Pump Motor Voltage (V)

Pump Motor Speed (RPM)

X-inclination (degrees)

Y-inclination (degrees)

Differential Inclination (Degrees)

Total Inclination (Degrees)

Pump Flow Rate (liters per minute)

Hole Fluid Pressure (MPa)

Hole Fluid Temperature (degrees C)

CPU temperature (degrees C)

Drill Motor Temperature (degrees C)

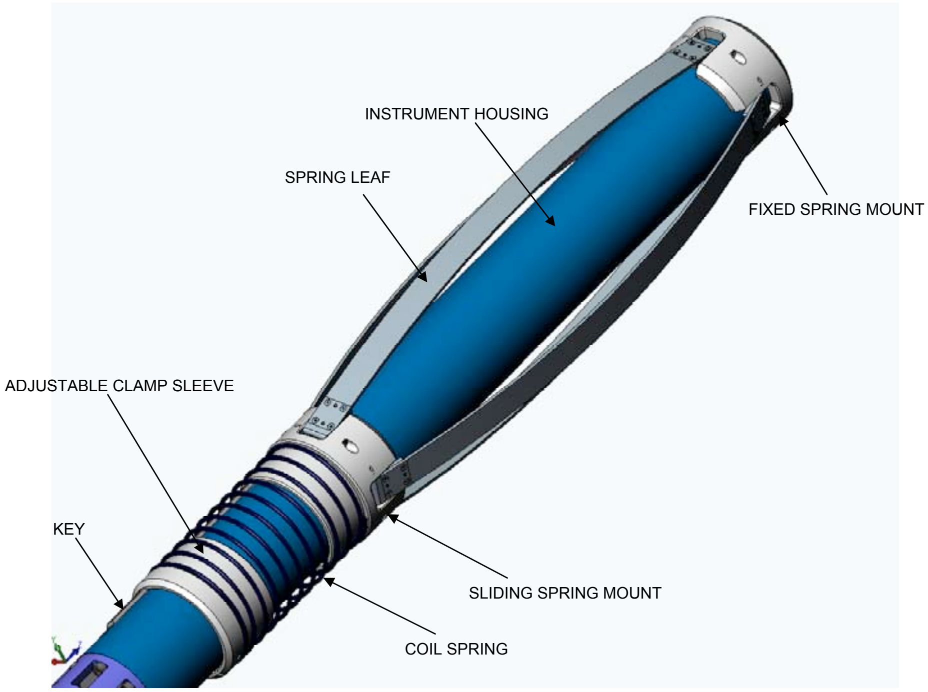


Figure 8 Instrument section and Anti-torque assembly8

Electronics And Instrumentation - Instrumentation requirements are in the process of evolution and are driven by ICWG-derived science requirements as well as by engineering considerations. The addition of an accelerometer was discussed and the team agreed that an accelerometer would be a helpful addition. Dynamic, closed-loop feedback controls are also under consideration. It is obvious that dynamic closed-loop control must incorporate devices not only in the BHA but within the winch control as well.

BHA Electronics - The heart of the BHA electronics is a single-board computer (SBC). The SBC performs multiple functions: it receives and decodes commands from the surface computer for running the drilling and pump motors and it also will receives motor and sensor data, formats that data, and send it to the surface in a continuous stream. The SBC will have an open structure so that it can incorporate other functions that arise in the course of design. See **Figure 9**.

Data transmission both up and down will be RS-485 through custom-designed and custom-built high-level drive circuits, probably at a rate of 9800 to 19,200 BAUD. Transmission will occur over two of the three available shielded and twisted wire-pairs. The third wire-pair is reserved for voltage regulation of the 300VDC power system within the BHA.

Motor speed, current, and torque will be gathered from the respective motor drives. A navigational package from Watson Industries will provide continuous data for plunge as well as azimuth (heading) of the BHA. The plunge readings derive from a pair of orthogonal accelerometers. The heading is derived from a 3-axis flux-gate magnetometer. This "Nav-Pack" is nearly identical to that used so successfully for 4 seasons in the AMANDA project. Communication within the instrumentation system, between the SBC and the NavPack, is in ASCII format over RS-232.

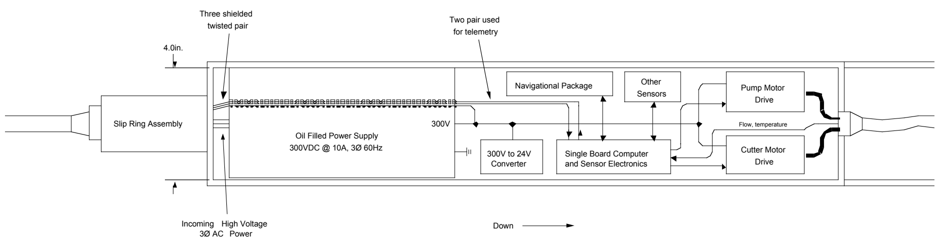


Figure 9 BHA Electronics

Other sensors include hole fluid pressure, which may be sensed by a Paroscientific quartz pressure transducer. It is accurate to 100 ppm over a pressure range of 0 to 6,000 psi (0 to 41 MPa). The corresponding precision is greater still. Temperatures are accurately measured with calibrated thermistors. Cutter load will be measured with a load-cell. A fluid-flow sensor is planned. A system to give early warning of drilling fluid leaks into the instrumentation chamber is required. Proposals for more exotic measurements -- such as core-barrel acceleration and flexing --- are being investigated.

Most of these sensor signals will require some analog processing. An analog amplification and conditioning printed-circuit board will be designed to sit close to the SBC and its on-board ADCs so as to minimize electronic noise, wiring, and packaging problems.

Motor and Pump section – The cutter-drive motor would be a custom designed brushless DC drill motor using a frameless HT03011, 500 rpm motor supplied by Hathaway-Emoteq, Inc., Tulsa, OK. It is coupled through a custom-designed and -made 4:1 planetary reduction to drive the outer motor housing. By using the motor shaft as the sun gear and fixing the planet gears, the ring gear imparts rotary motion to the outer motor housing. The non-rotating part of the motor housing is rigidly fixed and sealed to the instrumentation section. To resist crushing hydrostatic fluid forces and prevent fluid incursion, the motor will be completely filled ("pressure compensated") with a type of low-viscosity silicone oil.

Similarly, a silicone-fluid-filled ("pressure-compensated") brush-less DC-motor-driven pump will be mounted to the bottom side of the non-rotating motor housing. This pump, originally designed for deep-sea sampling applications, is a Model 212 supplied by *Tecnadyne Advanced Product Development*, Rancho Santa Fe, CA; it is capable of 946 l/min when used in an unrestricted configuration. For comparison purposes, this is more than 30 times the unrestricted flow capacity of the EPICA pump.

The pump motor is supported in position by the pump mount. A two-piece helical blade (propeller) is attached to the pump output shaft. The direction of rotation of the helical blade when pumping fluid through the drill is clockwise with respect to the sonde as viewed from the top. Below the pump is a well screen of 2” nominal diameter. These well screens are adapted from the groundwater production industry where they are used to protect wells and submersible pumps from the incursion of loose earth materials.

A mechanical adapter connects the instrumentation section to the (non-rotating) upper end of the drill motor (See **Figure 10)**. Within the motor adapter there is room for the Sea Con style connectors and cable that carries the power and control signals from the instrument section to the drill and pump motors. The lower non-rotating end of the drill motor is connected to the pump mount. A Sea Con style connector carrying power and signals to the pump motor and flow meter is located in the lower non-rotating end of the drill motor.

The drill motor’s outer (rotating) housing is fixed to the outer barrel on four narrow ribs which extent outward from the motor’s rotating housing to the inner surface of the outer barrel. This configuration provides an open channel for drilling fluid to flow *out* of the drill during downward tripping and while drilling core, and *into* the drill during upward tripping. A diffuser surrounds the pump propeller and connects to a flow meter.

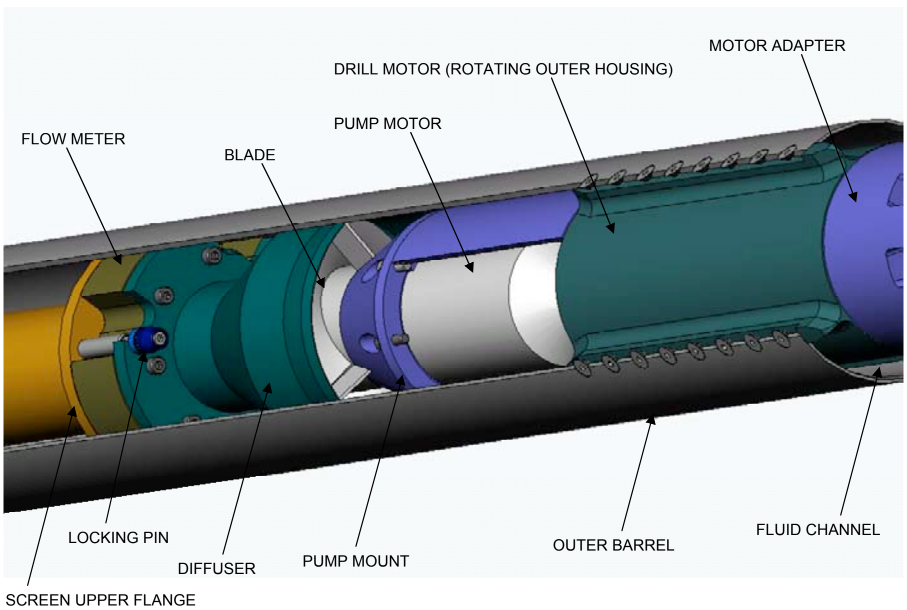


Figure 10 Motor and Pump

Well Screen (Filter) Assembly - The filter assembly slides inside the outer barrel of the BHA (See **Figure 11**). The filter assembly comprises an upper flange, a perforated torque tube surrounded by well screen, and a lower valve assembly. The screen section assembly is non-rotating, and is easily removed for cleaning

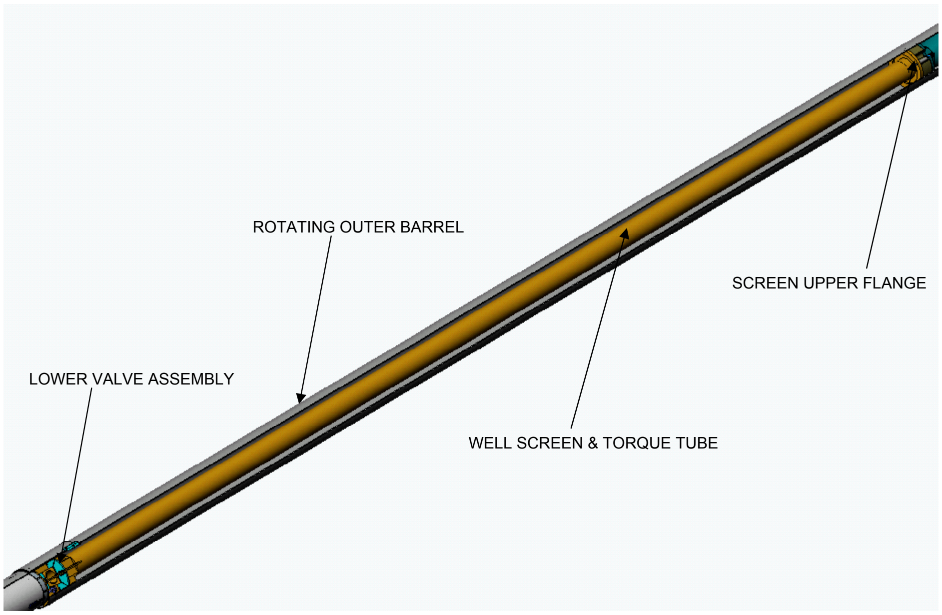


Figure 11 Well Screen Filter Assembly

Check valve – A check valve is located just below the well screen, and opens to permit fluid and chips to move up into the screen section. It does *not* permit chips to flow back out into the hole when the BHA is pulled out of the hole. The check valve is also useful when tripping the sonde into the hole as it allows fluid to be *pumped through* the sonde to maximize its downward speed. We envisage a typical a downward-tripping speed of 3 m/sec.

Lower valve assembly - The lower valve assembly, **Figure 12**, allows drilling fluid to be pumped through the drill when it tripped into or out of the hole. Two different situations arise:

1) As the drill is tripped *into* the hole, the pump moves fluid upward through an empty core barrel, the hydraulic pressure inside the core barrel is *greater than* the pressure in the screen section; the neutrally buoyant ball-type check valve seals against the screen closing off its inner bore. This causes the drilling fluid to take the path through the shutter-plate check valve and well screen mesh. See **Figure 13A**.

2) As the drill is tripped *out* of the hole with the pump running in the reversed direction, fluid is moved downward through the drill. Because the drill has a full core barrel and a full filter assembly, the hydraulic pressure inside the core barrel is *less than* the pressure in the screen section; the neutrally buoyant ball-type check valve seals against the core barrel, opening up the inner bore of the screen. This causes the drilling fluid to bypass the chip chamber entirely. The shutter-plate check valve is closed both by the weight of the chips in the chip chamber and by the fluid's differential pressure across the shutter plates. See **Figure 13B**.

At the lower end of the flow meter is the well-screen (filter) section. The screen's upper flange is sealed against the lower face of the flow meter. Quick-release locking pins hold the screen upper flange against the flow meter. These locking pins minimize the time required to disassemble the BHA for core barrel and screen removal. In our discussion thus far, the only rotating parts of the BHA are the drill motor outer housing, outer barrel, and the pump blade (propeller).

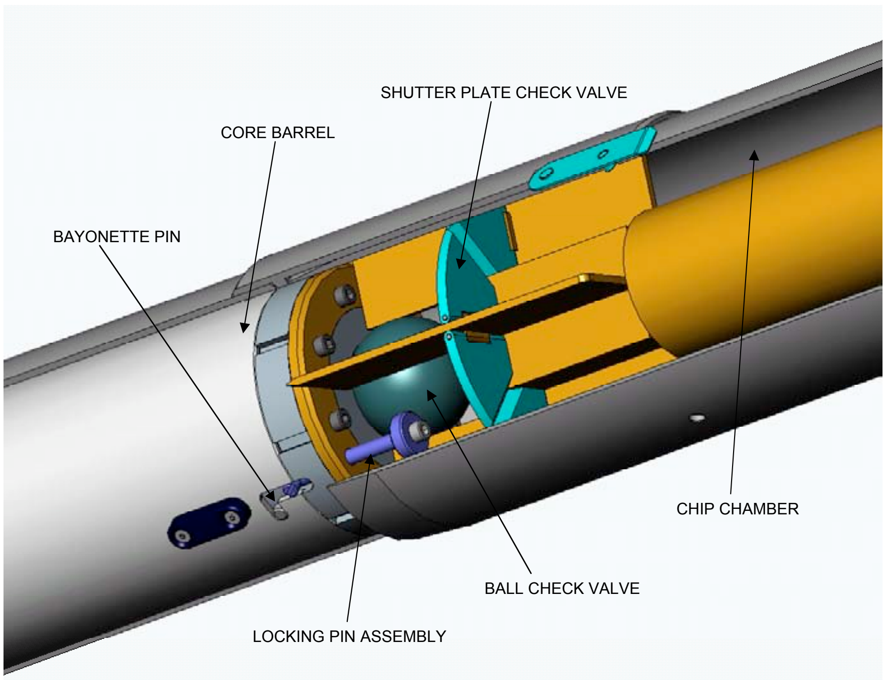


Figure 12 Lower Valve Assembly

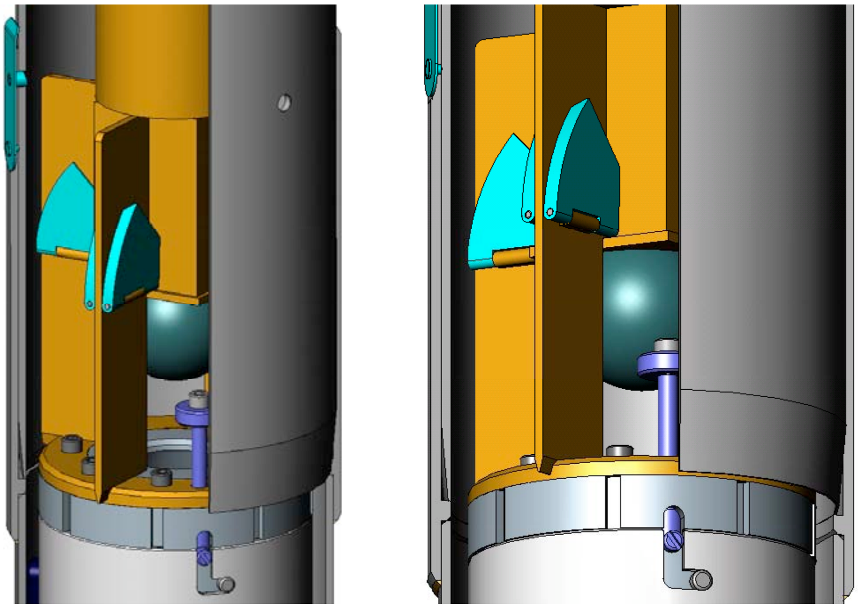


Figure 13A Drill tripping into hole

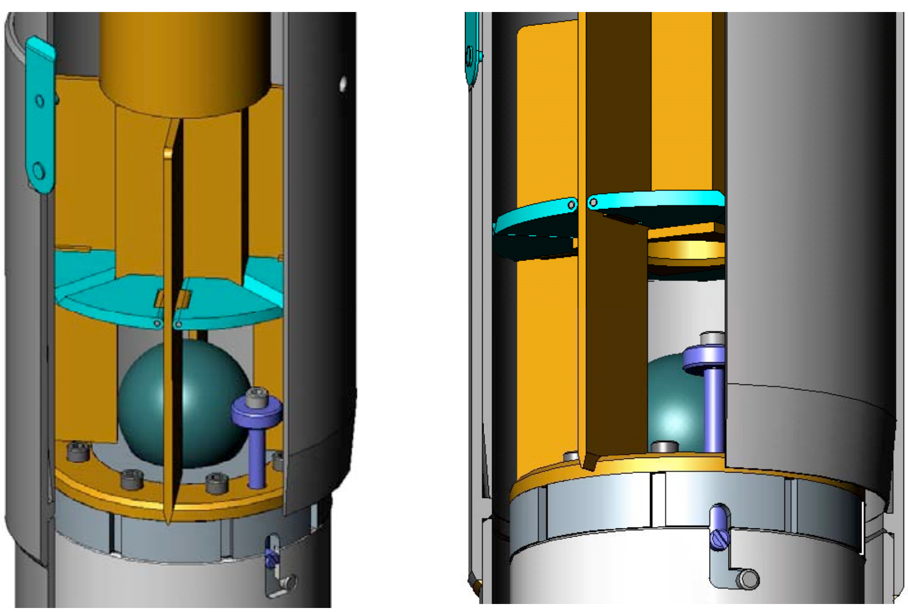


Figure 13B Drill trippin out of hole

Core Barrel Assembly - The core barrel assembly is shown in **Figure 14**. A key design feature of DISC is that the core barrel is *non-rotating*. The upper end of the core barrel attaches to the lower valve assembly of the screen by means of three bayonet pins and a quick-release locking pin. The core barrel is centered within the outer barrel using guide bosses located and spaced symmetrically at the top and bottom end of the core barrel. Chip transport occurs in the annular clearance between the core barrel and the outer barrel, and this radial clearance is 6.35 mm.

The cutter head retains the core barrel from dropping out of the BHA should it be unexpectedly unlatched. Many material and sleeve combinations are possible with this core barrel design. In addition, the BHA can be operated *entirely without* a core barrel, if additional stabilizers are used inside of the outer barrel to keep the core centered. In this case, however, the rotating outer barrel may at times ride directly on the core and put additional stresses upon it.

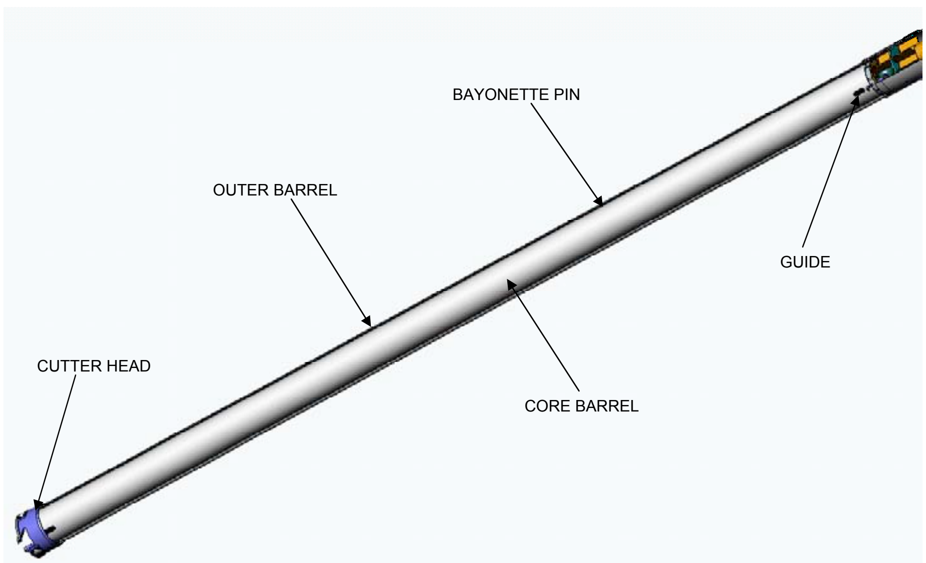


Figure 14 Core barrel assembly

Outer Barrel – The rotating outer barrel of the BHA rigidly attaches to the rotating motor housing. Channels and openings are provided for clear, filtered fluid flow through the Outer Barrel after exiting the filter assembly and pump. The rotating outer barrel of the BHA extends down to, and connects with, the outer flange of the screen section; below the screen section to the outer core barrel. Thus, rotary motion is imparted to the cutter head attached to the outer core barrel.

Cutter Head – Perhaps no other part of ice core drilling has engendered more (frequently heated!) discussion than cutter-head design. A variety of cutter heads have been used in the past, with mixed results. Most of them are based upon a helically grooved cylindrical base with replaceable razor-sharp teeth affixed to the distal extremity. Nearly all of these designs have three-fold, rotational symmetry but two-toothed designs also exist. The latter are usually confined to shallow, manually powered drills.

The DISC cutter head is likewise subject to discussion and research, and could be configured many different ways. The cutter head shown in **Figure 15** resembles a conventional design featuring the cutter blades, shoes, and core-dogs attached to the cylindrical body of the head.

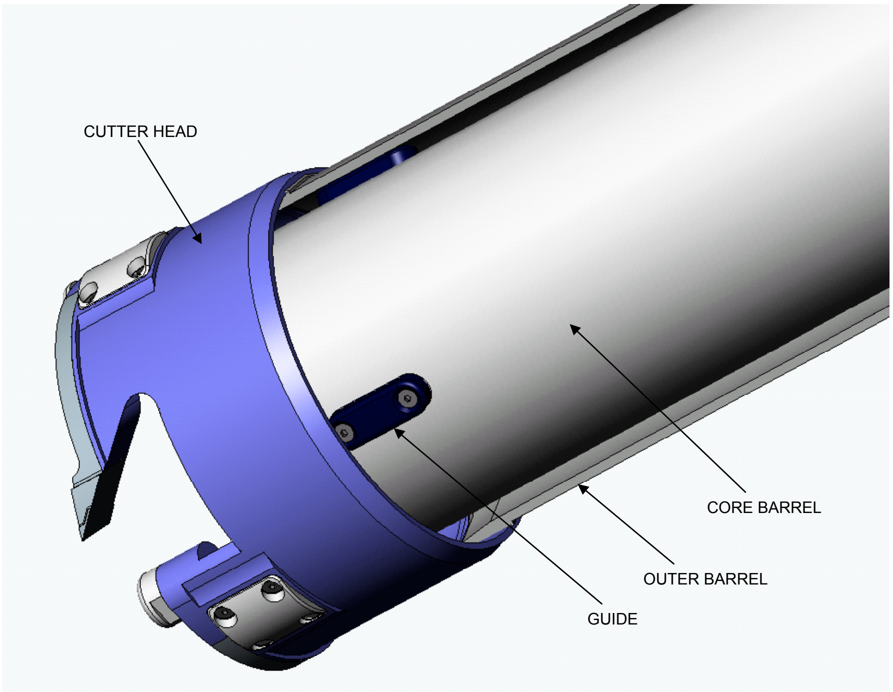


Figure 15 Disk cutter head

The various configuration options available to us can be tailored to special requirements found with different physical characteristics of ice, and our conception is for a modular system. For example, brittle-zone coring will likely require a different configuration of cutter geometry and core-dog than “warm” ice.

For our vision of DISC as a generational advance, existing cutter and head technology must be methodically analyzed and tested for applicability. The ability to explore configurations and tune the cutter head and core-dogs in a *modular fashion* is an advantage.

The cutter head is attached to the outer barrel. A threaded attachment is shown. The threads are a left hand helix since the direction of the cutter rotation is counter clockwise as viewed from the top of the BHA. This rotation direction has been chosen to help counter the pump motor torque when drilling. Note: the direction of pump motor rotation is clockwise during drilling. **Figure 16** shows the cutter head assembly from another angle.

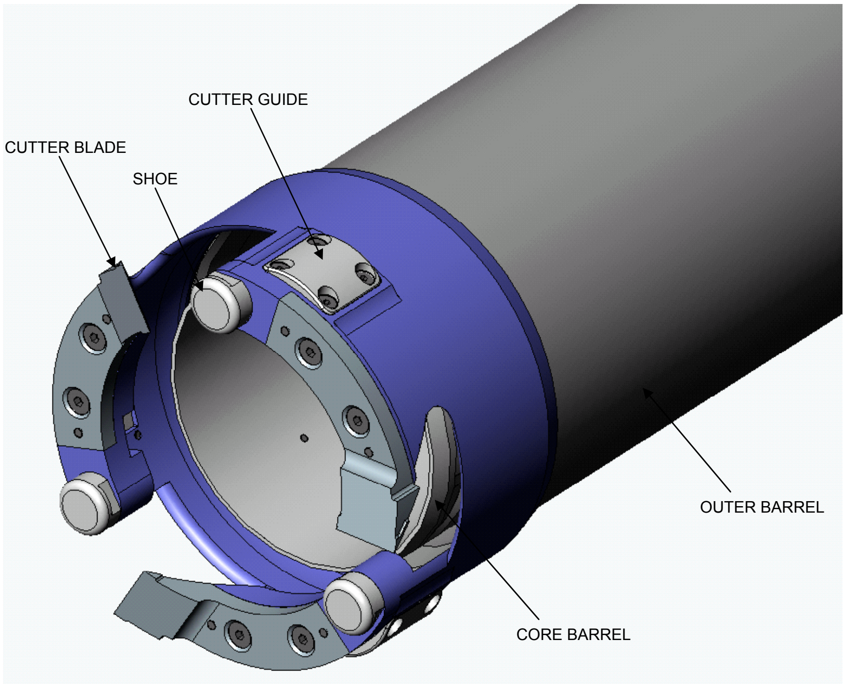


Figure 16 Disk cutter head

Note: the shoes have been positioned to help maximize the distance between the edge of the cutter and the face of the shoe. This will help reduce the sensitivity to ice buildup or chips caught under the shoe especially when drilling in warm ice where past experience has indicated that cutter pitch needs to be significantly reduced.

Also note: core dogs are not shown but they would be mounted in the cavity provided under each of the cutter guides. In practice, it may or may not be advisable to keep this cavity enclosed and so the cover will be made removable.

The cutter head opens up internally to provide ample chip-transport channel-ways.

Surface equipment: The surface equipment requirements and design is not finalized. There is continuing discussion regarding the merits of a tilting tower as the EPICA system, a modified carousel similar to the 5.2” GISP drill, or a rathole / trench modification for vertical assembly.

Here, we present one concept of a tilting tower for the DISC drill. **Figure 17** shows the sonde and tilting tower in the vertical (“ready-to-drill”) position. **Figure 18** shows the BHA and tilting tower in the horizontal (core-handling) position.

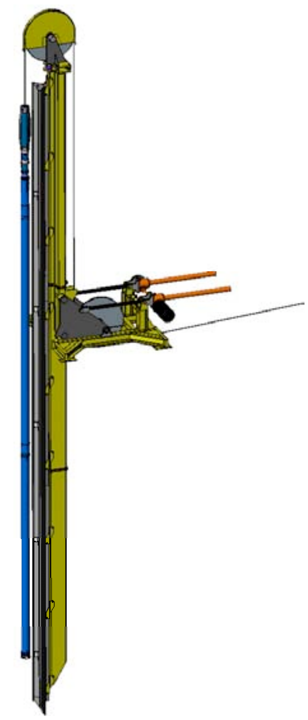


Figure 17 Sonde and tilting tower - vertical

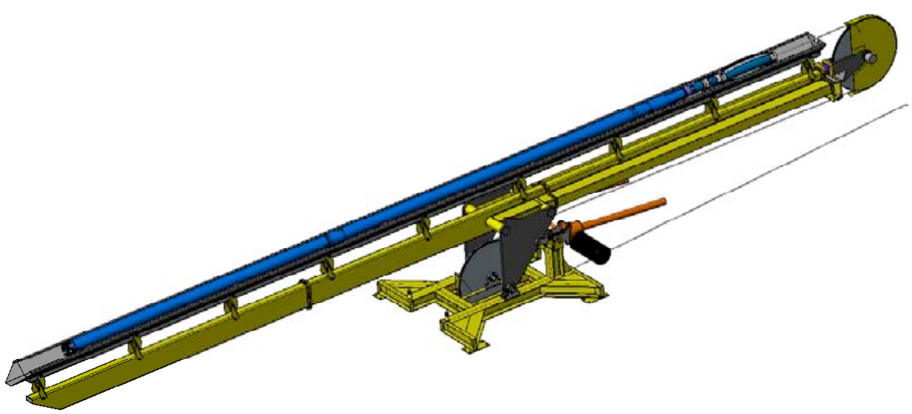


Figure 18 Sonde and tilting tower - horizontal

Surface Power and Control: A PC-type computer at the surface will monitor and orchestrate the entire drilling operation. This computer sends commands down to the sonde's SBC (Single Board Computer) to control the cutter and pump motors, while simultaneously receiving and decoding a continuous stream of digital data from the sonde's SBC. This data stream will contain all motor and sensor information.

The 480V, 3Ø, 60Hz generator's output, in addition to feeding the step-up transformer discussed elsewhere, also powers a variable frequency motor drive. This drive, in turn, runs the winch motor - a powerful and rugged 3-phase induction motor. Encoder feedback from the winch motor to the drive ensures smooth speed control at very low rpm operation - necessary for fine rate-of-penetration control. All winch speed and torque profiles will be performed by a flux vector (variable frequency) drive under the command of the surface PC-type control computer. This system will essentially mimic the most sophisticated versions of the EPICA winch drives currently in use (for example, at DML).

A computer controls the winch in closed-loop (i.e., using feedback) mode, detecting payout and speed from encoders mounted on the crown and lower sheaves as well as load-cells under the crown sheave. Redundancy resulting from multiple encoders and load-cells allows the computer to compare related inputs, ensuring high reliability and safety of operation. For example, limits can be placed on the maximum deviation allowed between a pair of load-cells measuring the same load thereby detecting out-of-specification failure. Lacking redundancy, total failures are the only ones that would be detected; one can imagine catastrophic consequences as a result.

A high-voltage slip ring will carry the 3Ø power to the wireline cable. The same slip ring will handle signals on three (3) shielded and twisted wire-pairs.

The control computer will display all relevant data on a large high-resolution color monitor in a format that is easy to read. Coarse and fine control, digital shaft encoders may be used for tactile (manual) control of critical parameters such as penetration speed. All drilling data will be automatically logged on the computer's hard drive providing a continuous digital record of each and every drill run that can be overlaid (later) with the logging records of researchers working on the core. Comments may be added to the electronic record by the driller(s) via the keyboard. A hard-copy snapshot of system status may be generated at any time using "screen capture."

Control software and operating system has not yet been selected. There are many commercial packages for oil industry drilling that could be used as a base. An attractive option would be to use the software base presently being developed employing NSF funds for the Enhanced Hot Water Drill. In any case, it is certain that the top-level application layer will have to be customized to control the unique DISC drill.

Power and Wireline System - The DISC design calls for 3kW of power (utilized internally as 10A at 300 VDC) to be delivered to the BHA. Delivering the power as 60Hz, 3-phase AC offers low conductor loss, minimal ripple in the BHA (following full-wave rectification to DC), and compatibility with commercially available generators.

A tentative wireline cable-design has been identified. The cable has three power conductors (one for each of 3 phases of the 3Ø power) and three shielded / twisted pairs of wires for telemetry and voltage feedback. The overall diameter of the cable is approximately 1.57 cm (0.62 inches), with a weight (in air) of 0.89 kg/m (0.6 lb/foot) and a breaking strength of 111 200 N (25 000 lb-f).

A design goal is that the power lost in the cable be held to about 10% of the power delivered -- about 300 W over a design length of 3,800 meters. This requires transmission of power at fairly high voltages / low current to minimize resistance-related losses. Of course, it follows that the electrical insulation for the three power conductors must withstand these high AC voltages and the design of the cable (referred to above) embodies this criteria.

At the surface, power is supplied from an industry-standard 480V 3Ø 60Hz generator. A multi-tap 3Ø transformer steps up the 3Ø input voltage. The input taps are selected by monitoring a supply voltage feedback signal from the. Semiconductor devices that commutate at zero crossings electronically switch the taps. In this way, the high voltage input to the 3.8km power conductors can be dynamically adjusted to compensate for varying load currents and provide a relatively steady 300VDC at the BHA.

The 3Ø AC power is delivered to a transformer in the instrumentation section of the BHA. This transformer steps down the high voltage and delivers it to a 3-phase full-wave rectifier bridge. In this way, low-ripple 300VDC can then be directly supplied to the cutter and pump motor-drive electronics, and will also power a 300V to 24V DC-DC converter. The 24V output will power all the processing and sensor electronics in the instrumentation section of the BHA.

PERFORMANCE OF THE DISC DRILL

Tripping -The tripping rate will be up to and beyond 2 meters/sec. This will be accomplished by utilizing a number of techniques. The annulus between the outer core barrel and the borehole wall will be increased as much as is practical. This will depend on core diameter, available tubing sizes, minimum cutter kerf requirements, and inner and outer core barrel annulus. The exact, specific core diameters are necessary to finalize the list of options that can be optimally incorporated into the new design. Some trade offs are necessary because some techniques for maximizing trip times conflict with others.

Mobilization - Every effort will be exercised to minimize core rig mobilization times. Hinged and tipping components will be used to help reduce mobilization and demobilization times. It is intended that the drill superstructure be removed between seasons to minimize drifting around the borehole and to reduce the level of put-in efforts.

Bedrock Coring - Rock-coring efforts will be limited in depth. An AQ size (48 mm OD bit / 31 mm core) diamond rock-coring bit should be used. This will allow the use of the existing drill motor and instrument section without additions or serious modifications. A depth of 5 meters would be the absolute maximum target depth. A larger diameter BQ size (60 mm bit / 41 mm core) core might be recovered but this could require minor modifications. This rock-coring operation would require the construction of a separate rock coring subassembly, attaching to the existing motor section via a standard drill coupling.

Experience gained during the rock drilling efforts at GISP, Taylor Dome, and Siple Dome assures a high probability of success with minimal operational risk.

12.2 CM DEEP ICE SHEET CORING DRILL

At the July 2002 team workshop, the team reexamined the 10 cm concept. There were some engineering packaging and part selection reasons for discussing the larger diameter. From an engineering design standpoint, the larger diameter allows for more selection of “off the shelf” parts to be used for the internal parts of the BHA. The packaged of the parts in the smaller BHA would be special designs, which will add cost to the overall drill system.

However, what really triggered the discussion was the risk of replicate coring. At the 2001 ICWG meeting held at “the Biosphere,” the ICWG decided that 10 cm core would be adequate, were replicate core to be drilled through sections of special scientific interest. With the realization that replicate coring with a mechanical ice coring drill has never been accomplished, the team allowed that replicate core may be challenging to recover. The discussion then focused on how best to mitigate the potential replicate-coring-system failure with concurrent loss of science opportunities due to lack of sufficient ice volume to perform the required analyses. This debate is ongoing within the ICWG.

SCIENCE PERSPECTIVE

Need for replicate coring….

Replicate cores are collected from a second borehole that is close to and parallel to the borehole the main core was collected from. The general concept is to lower the drill into an existing borehole and drill through the side of the borehole so that a second borehole is made that deviates from the first borehole. This is a standard operation in the petroleum industry. The ability to collect replicate cores from depths of special interest is required for the following reasons.

1) Additional types of measurements can be made that could not be made on the original core due to a lack of ice.

2) Measurements that were made on the original core can be made with a greater time resolution on a replicate core because more ice will be available.

3) Measurements that were made on the main core can be verified with ice from a replicate core to confirm anomalous results are accurate and not a measurement error.

4) There is a second chance to collect ice that had unacceptable core quality when the first borehole was drilled.

As analytical methods less ice for each type of measurement was required. However, a trend to increase the number of different types of measurements that are made and a trend to increase time resolution as key science questions evolve, requires increasing the frequency of measurements. Over all the demand for ice volume in areas of special interest is increasing not decreasing.

Selection of core diameter for the DISC drill

The engineering and logistics impacts of a larger core are considered elsewhere. This section concerns the scientific implications

Expanded Science Opportunities: One of the most powerful advances in ice core analytical methods is the development of techniques to slowly melt the ends of 1 meter long sections of ice cut along the axis of the core. These longitudinal samples of ice are melted and the melt water is feed into analytical instruments. (Rothlisberger et al., 2000; McConnell et al., 2002a; 2002b) Typically the longitudinal samples of ice have a square cross section and are 2 to 3 cm on a side. The exterior portion cannot be used for chemistry measurements because it may be contaminated by cutting and handling, so it is isolated and discarded during the analysis. When melting samples with a cross section of 2.5 x 2.5 cm, there is an interior cross section of ~2.2 cm^2 that is available for chemistry measurements and the mechanical strength of the sample becomes a serious concern. When melting samples with a cross section of 3 x 3 cm, there is an interior cross section of ~4 cm^2 that is available for chemistry measurements and the mechanical strength of the ice is of less concern. The greater interior cross section of a 3 x 3 cm sample almost doubles the usable sample compared to a 2.5 x 2.5 cm sample. This allows more measurements to be made on the same sample and reduces the problems associated with melting the ice in different labs and then co-registering the results.

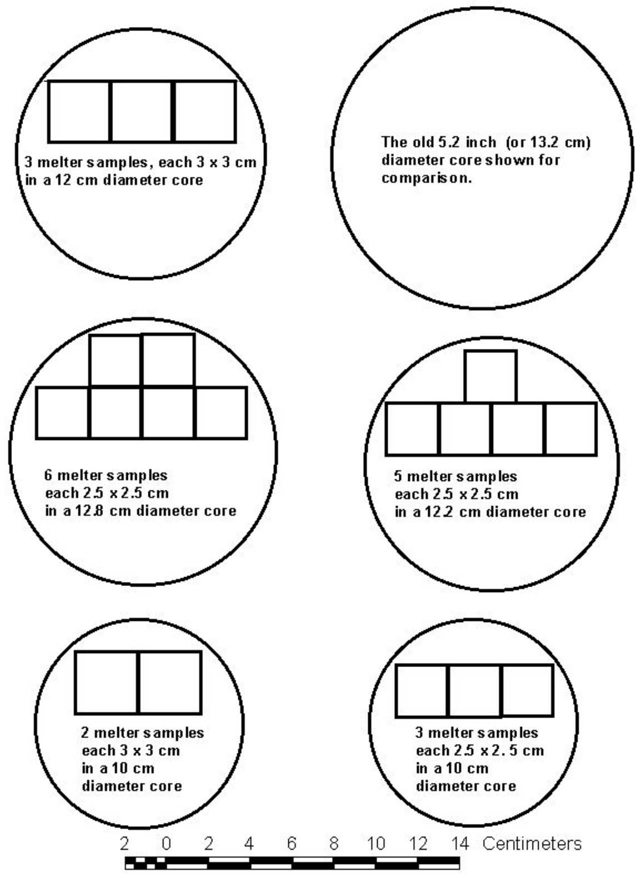


Figure 19: Ice Core Cutting Plan

Measurements on different sections of the same core are made over a period of months or years. To increase the confidence in the consistency of these measurements it is necessary to measure about 30% of the core twice. For example the first meter of ice that is analyzed each day typically comes from the same depth as the last meter of ice that was measured on the previous day; and after making measurements all the way down a core it is common to rerun ice from every tenth meter. This replication of measurements greatly increases confidence in results. The selection of the diameter of the core is strongly driven by the ability to cut the core into longitudinal samples of ice. The first cut along the axis of the core must be off the central plane of the core so the core can be clamped down at the widest point when it is laid horizontally. (If it is clamped down at a point that is not at the widest point it will pop out of the clamp.) There also has to be sufficient ice for gas analysis that currently do not use a continuous section, and for an archive for future measurements.

Figure 19 shows possible cut plans for different core diameters and **Table 2** summarizes the results for core diameters that are can be efficiently cut into convenient samples.

Table 2: Ice Core Cutting Table

Core diameter	Stick size	Number	Number of melters that can be used	Cross section for gas analysis and archive
(cm)	(cm)	of sticks		(cm^2)
10	3	2	1	38
10	2.5	3	2	34
12	3	3	2	61
12.2	2.5	5	3	43
12.8	2.5	6	4	59

CAMP OVERVIEW AND LOGISTICAL ISSUES

The integration of the logistics contractor into the coring program from the beginning of planning is critical to the success of the project. If the logistics coordinator were involved throughout the design process so that the coring needs are adequately understood clearly streamlines the operation and is will lead to cost savings. GISP2 coring and logistics was done with the same contractor, and hence logistics was considering at the outset of the operations. This had many advantages that were noticeably absent during the Siple Dome coring efforts.

The proposed inland coring program will be fully integrated with the supporting logistics. The success of the inland coring program is directly tied to the camp logistics. The operational tempo of the inland coring program sets that of the supporting camp and the logistics of the site determine the operational tempo of the inland coring program. Since both are linked, operations will require the holistic approach of project management to succeed in the desired amount of time.

The plan is that the drill would hit bedrock within two seasons. This would entail a five-year total time at site. This is an ambitious project to reach this target as the projected site might be about 900 nm from McMurdo and is at the end of the world's longest logistical chain in an area of currently unmonitored weather conditions. The timeline for Antarctic work is as follows:

Year 1: Setting the Stage

The first year of the inland coring project would be an infrastructure staging and facilities configuration mobilization. This season would be the first full systems test of the camp infrastructure and a critical season to work out any problems and fine tune the camp for easy set up the following season. The bulk of fuel and coring fluid would be staged at the camp in addition to as much of the core handling and coring systems as feasible. The exact mix of logistics (combination of LC 130 and traverse options) is undetermined. But, there would be a primary push to move dumb cargo (coring fluid, fuel, structures) overland and fly in the smart cargo (people, scientific gear, sensitive components). The initial surface coring through the firn and surface casing setting would also take place.

Also, two 50 meter dry drilled boreholes would be drilled located up to 30 km from the camp. The purpose of these cores is to investigate the influence of ice accumulation rate on the atmospheric deposition of chemical compounds.

An 80 m, 4 inch diameter core will be drilled at the main coring site to assure continuity between the dry drilling used to set the surface casing and the wet drilling used below the surface casing. Because an ice slurry is used to seal the bottom of the casing, the ice slurry adversely impacts a few meters of the record from the main borehole. This core would be drilled in the first drilling season when the surface casing is installed. This core would also provide additional ice in the firn where the science needs cannot be meet with just the ice from the main core.

Year 2 and 3: Core to Bedrock, Core Retrograde

These two seasons would involve extended field seasons to core to bedrock. As much core as scientifically and logistically feasible would be retrograded. There would also be some borehole logging activities.

Year 4: Replicate Coring, Bedrock Coring, and Core Retrograde

This season would involve the replicate coring, bedrock coring, and the brittle ice core retrograde. This year would also be a more traditional field season at a somewhat reduced operational tempo. More borehole logs would be run. Borehole wall smoothing could be done if optical logging shows that the wall is too corrugated. This may require a tool to polish the borehole wall.

Year 5: Core Retrograde and Dismantle Camp

This season would see the retrograde of any remaining core plus the dismantling of the drill site and main camp to an as of yet to be determined location. The flexibility of the camp would allow it to be transported to another location and for us take advantage of ease of set up that it provides.

For the project to succeed in this time frame, one main logistical hurdle needs to be addressed and overcome. This hurdle is how to provide an extended field season to maximize coring time on site. With a targeted goal of five years any additional seasons would take away airlift capacity and resources from an already limited USAP pool. In theory the drilling time would be from 120 to 140 days over two extended field seasons. There are several concepts that need to be developed to provide an extended season. These concepts are contingent upon each other for a successful coring program.

First, the camp infrastructure needs to incorporate a heavy emphasis on prefabricated structures that are conducive to easy set up and take down. Traditional put-in's for large camps require many people, time, and materials for set up. This erodes an already short Antarctic deep field season. The infrastructure of this Inland Site camp would involve several types of prefabricated modules that would be configured and tested in the United States. Once at the site it would take a minimal amount of time and effort to set up and tie in electrically and structurally as needed. Several manufactures currently design and fabricate such structures; Weatherhaven, ATCO, Bally, and Sonic Enclosures among others. The key for this is to identify the requirements early, design, and procure such structures in a timely fashion in anticipation of this project. These units would not entirely replace the traditional field structures but replace the most labor-intensive components with efficient units that allow for quick set up for life support and drilling operations. Ideally, prefabricated modules would be used for the galley, ablution, control aspects of the core handling facilities including the butyl evaporation units in addition to electrical generation and refrigeration modules. The design of this modular / traversable camp would also include enough heavy equipment to support it at the site.

Ideally, the original designers and planners involved in the project would also be involved in the on-site set up to transfer the thinking behind the designs to the camp staff, drilling, and core handlers. This would also help resolve design and configuration problems prior to the heavy second year.

The second concept is a smaller put-in crew to mobilize the life support and begin skyway-grooming operations prior to the initial LC-130 landing. The first LC-130 to the site would include drillers and staff to focus primarily of the rig up of the coring camp. One possibility that needs further investigation is having an early season Twin Otter put-in to the inland Site. There are still quite a few unknowns for this extended season approach to work; but rethinking the traditional approach to deep field operations is a good way to start.

MAIN CAMP AND POPULATION CONTROL

The estimated population to provide science, operational, drilling, and core handling support indicates that the heaviest population spike will be the second year of operations (see **Figure __**). This second year spike is associated with the initial short trip times for the coring and operational tempo for that includes three tours a day and the related support requirements. The number of people (46) is not an excessively difficult number to support with the right infrastructure. However, the support requirements rise exponentially as more people are included. This scope creep should be monitored especially in the second and third seasons to maintain the lowest amount of population required as to keep the logistics load from overwhelming operations. Most of the population will require some sort of berthing and any additional people beyond the planned for size would increase the amount of resources at the camp.

Other key points pertaining to the camp:

- Use of wireless IT solutions to integrate drilling with core processing
- Inclusion of alternative energy into the design of the drill and main camp

- Use of prefabricated structures for electrical generation housing
- Possible capture of waste heat from generators for heat or water production
- Possible use of a Rodriguez well for water production
- Cross training of Science, ICDS, RPSC and NICL personnel for a team approach to the project
- Centralized refrigeration units in a dedicated structure at the drill site
- Possible use of tunneling technology to eliminate all or some of the trenching and the associated logistics
- Integration of management at site with an established clear chain of command to set clear goals and responsibilities and to provide a healthy, safe, productive working environment
- Use of professional project management practices for planning, scheduling and controlling
- Apply lessons learned in the Greenland test to the Antarctic component
- Use the collective knowledge from past coring projects to improve future projects.
- Drill design to minimize the need for heavy equipment.
- Prefabricated control room for drilling operations.
- Support facilities for machining and supply on site.

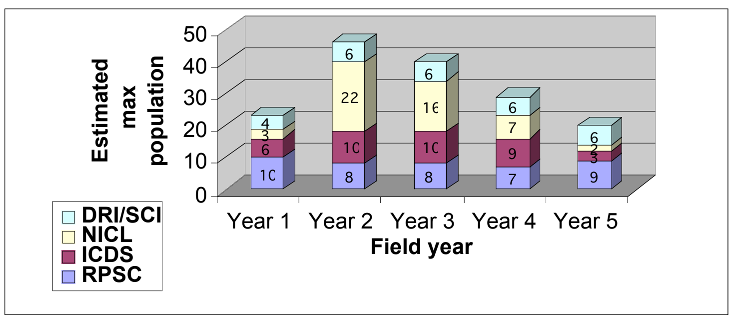


Figure 20: Projected Inland Camp Population

Core Handling

Regardless of the core rig option, the core handling once the core is horizontal is identical. The National Ice Core Laboratory (NICL) has been given the task of developing and implementing the ice core handling system. There is no plan to develop a significant science measurement operation as was done in the GISP2 operation. The National Ice Core Laboratory (NICL) will be the ultimate repository and scientific laboratory. Only those science items that are time critical will be done on-site.

Core handling is a time consuming and expensive task. The main thrust of the system proposed here is to limit the number of times the core is handled and moved at the drill site and through the long shipping process and to increase the amount of core per cargo flight that moves core from drill site to coast. The core handling system proposed by NICL addresses the onsite core handling procedures, shipping from the drill site to NICL, data acquisition, and storage. There are also ideas for saving time and money. The main goal of this system is to streamline on-site core handling, speed up butyl evaporation from the ice cores, decrease the movement of individual core trays, recommend a dense packing and shipping container delivery system, decrease man hours needed in the field and at McMurdo to shuttle ice core containers, decrease the number of flights needed for ice core shipping, and speed deployment and pack up of all core handling equipment in the field.

Core handling is a vital component of any deep core-drilling project. The proposed Inland Core Project would core approximately 80 meters a day at maximum capacity and to a depth of 3,800 meters. This coring is proposed to take place over two seasons, plus a third season of replicate coring. A total of more than 4,500 or more one-meter tubes may have to be handled, cut, logged into a database, butyl removed, stored on site, and packed and shipped back to the National Ice Core Laboratory (NICL).

The core-handling goal for team review was to minimize the number of times an ice core is handled. The plan is to lay down the core, gently remove it from the core barrel, and immediately give the drillers feedback on core quality and length. The use of buffers (points for the temporary storage of core during overload times) at critical junctions will be vital to the success of core handling operations.

Another point of critical consideration is the cleaning of coring fluid off of the cores. The current plan is to use n-Butyl Acetate, although there is ongoing research into alternative fluids. If butyl is used, then there must be a three-day de-butylization buffer for evaporation of the fluid. This requires a substantial building, refrigerators, and blowers.

Prior to cleaning, the cores would be cut to 1 meter lengths and loaded on racks. These racks are being designed to cradle the core from that point until they arrive at NICL. All core activities would take place in the racks. This minimizes the core handling times by humans.

Once the coring fluid is removed, the cores are sent to either short or long time storage, for ductile and brittle ice, respectively. The structure of the storage facility is still being debated; however, the decision is between surface facilities, a trench, or a tunnel.

Within the storage facility, the cores would be prepared for shipping to NICL. The cores, still in the racks, would be packed and boxed onto standard C 130 pallets. This concept is based on a new high density-shipping container that once packed in the field, would not be unloaded until the container arrived at NICL in Denver, Colorado. Each container would be loaded into a refrigerated Milvan at McMurdo for shipment off the continent.

NICL would also develop a single common database for every core accessible by all parties on site in the field. The core handlers, scientists, and the drillers would use this common database. This would allow all interested parties to identify the individual cores and their coring history, coring operational parameters, and field observations.

The National Ice Core Laboratory has been given the task of developing and implementing the ice core handling system for the Inland Drill Project. This task is by no means small and needs to come to fruition in the next two years. However, NICL believes that a comprehensive core handling system can be implemented, and can take into consideration all of the necessary phases of core handling, from the deep drill site to NICL, and through the subsequent core processing line at the National Ice Core Laboratory.

Core handling is a time consuming and expensive task. The main thrust of the system proposed here is to limit the number of times the core is handled and moved at the drill site and through the long shipping process, and to increase the amount of core per cargo flight that moves core from drill site to coast. The core handling system proposed here by NICL will address the onsite core handling procedures, shipping from the drill site to NICL, data acquisition and storage, and ideas for saving time and money. This system could streamline on-site core handling, speed up butyl evaporation from the ice cores, decrease the movement of individual core trays, provide a dense packing and shipping container delivery system, decrease man hours needed in the field and at McMurdo to shuttle ice core containers, decrease the number of flights needed for container shipping, and speed deployment and pack-up of all core-handling equipment in the field.

National Ice Core Laboratory-NICL, and staffing needs

The National Ice Core Laboratory was established in 1993 as a repository for ice core samples of meteoric ice collected from polar and high altitude regions of the globe. It has operated successfully under a joint funding agreement between the National Foundation (NSF) and the United States Geological Survey (USGS) since 1998. The collection has grown annually to nearly 13,000 tubes representing nearly 14 kilometers of ice. In addition, the NICL has successfully hosted many Core Processing Lines (CPL) during which core collected earlier in the season was sampled.

As the final repository for ice samples, the NICL has a vested interest in the logging and acquisition of information regarding the quality of all measurements regarding drilling and drilling procedures. Such information recorded in the field will be used in conjunction with the related core as long as it remains in the collection (and sometimes beyond that time), and is essential to NICL for providing accurate and precise depth values for sampling. Involvement of NICL during the accession process allows for a seamless acquisition of metadata from site to repository, and would accurately track the core data, increase accessibility, and ultimately provide the quality information necessary for sampling.

Well-planned database standards from the drill site will allow integration into the NICL database system, ensure continuity of metadata from site to repository, maintain accurate tracking, increase accessibility, and ultimately provide quality information necessary for sampling.

The National Ice Core Laboratory currently stores 12,943 tubes of ice. A projected 4,500 tubes of ice generated from the Inland drill site would arrive at the NICL by the year 2008. 4,500 additional tubes of ice represent an increase of 35% to the NICL inventory. 3,676 tubes of ice or 28% of the total have been inventoried in the last few years. Thousands of samples are processed and shipped each year. A Core Processing Line, or CPL, has been run each and every summer. Thousands of people tour the NICL each year and dozens of scientists sample and conduct research at the Lab.

Current and upcoming NICL projects include the following:

- Continued inventory of remaining core tubes.
- Development of a digital camera system for one-meter cores, collection and storage of terabytes data from one-meter digital camera system.
- Continuing database construction upgrades and refinement.
- Implementing a shipping and tracking database.

- Addressing storage space and shelf upgrades that must take place prior to any large ice core shipments to the NICL.
- Conducting ITASE CPL and sampling.
- Training interns needed for CPL and general NICL duties.
- Addressing continual maintenance requirements for the NICL refrigeration system.

During the first season two NICL representatives will provide supervision at the drill site and will ensure appropriate construction and operation of core handling and processing equipment. A total of 13 to 15 core handlers may be needed for the second drill season (drilling from 60m to 1,800m) and NICL staff would be required to manage the onsite drill handlers and database. The third and fourth drill seasons would require 8 to 10 core handlers, assuming each core handler stays the full season. Graduate students will be granted the opportunity to offer their services as core handlers for a half season or longer; therefore, an equal number of replacement core handlers will be trained and prepared to offer their services in the field at that time.

It is recognized by NICL and has been previously addressed by NICL and NSF that additional workload would require additional staff. While current responsibilities are large, an increase in projected responsibilities will overtax the present staff at the NICL. The Inland drill site would require two additional NICL staff members to develop and implement a core handling system. NICL staff would be required to train CPL participants and up to 20 drill site core handlers annually, and NICL staff would be required to manage the onsite drill handlers and database. The staff requirements for the Inland drill project would be the same if another science entity took on the core handling responsibilities.

PROPOSED ENHANCEMENTS TO THE SHIPPING CONTAINERS

Inland drill site Allowable Cargo Load

Raytheon’s estimates are that the Allowable Cargo Load (ACL) departing the Inland drill site is 15,000 lbs per flight, or no more than 4,000 lbf per pallet. Of the 4,000 lbf, the Air Force pallet itself weighs 400 lbf resulting in a maximum cargo weight of 3,600 lbf of ice and packing material shipped from the Deep Ice Sheet Core project site.

Insulated Shipping Containers (ISC) Currently In Use

Insulated Shipping Containers, or “ISC” boxes, have been used in the past for shipping ice cores from the drill site to their final destination at the NICL. These can hold four 13.2 cm cores or six 10 cm cores. The containers were designed to be hand carried by two people. At 124 to 128 lbf each, these core boxes could be manually packed and then stacked onto aluminum Air Force pallets for delivery to McMurdo Station.

Two sized of ice core are being considered for the DISC project, 10 cm and 12.2 cm core. For 12.2 cm core, new ISC boxes would have to be ordered to assure correct fit of tubes in the boxes. The current cost is approximately $80 to $100 per container when purchased in bulk. The NICL estimates that 1,600 ice core tubes may be shipped after each of drilling seasons three and four. At a minimum, 340 containers for the 10 cm tubes or 400 containers for the 12.2 cm tubes would be needed for shipping for seasons three and four.

After loading the ice cores into the tubes, the containers would be stacked on wooden pallets and sent on the cargo flight back to McMurdo station. Once at McMurdo, each wooden pallet would be placed into the McMurdo freezer units.

Proposed High-density (HD) Shipping Containers

Substantial time savings could be achieved and the core handling process improved by using new shipping containers tailored to Air Force pallets. These containers would be approximately 95 cm wide, 1.1 meters high and 1.2 meters long, and would have 5 cm of insulation around the outside, as well as insulation between each core tube for thermal and shock protection. Thirty 12.2 cm tubes and 40 10 cm tubes would fit into each shipping container. Using new HD containers, a total of 120 12.2 cm cores or 160 10 cm cores, or four shipping containers, would fit onto each Air Force pallet.

The individual high-density shipping containers would be stored directly at McMurdo in refrigerated “milvan” shipping containers. Eliminating the need for Raytheon to build freezers to accommodate this large quantity of ice generated from our coring operation would represent a great cost saving advantage to the NSF and the scientific community.

Furthermore, the refrigerated milvan shipping containers could be placed directly on the cargo ship for the trip back to CONUS. In California, the milvans would be loaded directly onto trucks and driven to the NICL for unloading into our freezer.

In summary, pallets could be packed in the field and not unpacked again until the CPL at the NICL, saving valuable time and hundreds of staff-hours at the drill site and throughout the shipping process. If the NICL interior storage could not accommodate this large shipment, the milvans could even be left at the loading dock and used for temporary storage. **Table 3** outlines the shipping options.

The use of the proposed high-density shipping containers would reduce the number of cargo flights to the drill site. If the old ISC boxes were used, 1,125 would be needed for the 12.2 cm core, requiring 28 pallets, each containing a maximum of 40 empty boxes. Alternatively, adoption of high-density shipping containers would require 150 containers over the life of the project, and since these containers can be double-stacked on the pallets when empty only 19 pallets would be required. A savings of nine pallets or roughly two entire cargo flights to the drill site can be achieved using the high-density shipping containers.

For the case of 10 cm core, 750 ISC boxes and 19 pallets would be required over the life of the project. However, only 14 pallets would be required when using the high-density shipping containers, a savings of one entire cargo flight to the drill site.

Mobile Expandable Container Configuration buildings - (MECC)

Mobile Expandable Container Configuration units, or MECC, a trade name of the Weatherhaven Corporation of Burnaby, BC, Canada, are being considered for the drill site surface core handling buildings. These units would be outfitted at the National Ice Core Laboratory in the United States with all of the equipment needed for the onsite core-handling requirements. When fully equipped and tested at NICL, these units will be packed up and deployed to the field ready for quick onsite setup. When fully

Table 3: Comparison of the Current and Proposed Shipping Containers

Weights are in pounds

Container	Number of cores per container	Total ice weight per container	Container and packing weight without ice	% ice weight of each container	% packing weight of each container	Total box weight with ice and packing	Total number of containers per project based on 4,500 tubes	Total ice core shipping weight for project based on 4,500 tubes	Total number of flights required for project*
ISC 10 cm	6	96	32	67	33	128	750	96,000	6.4
ISC 12.2 cm	4	92	32	65	35	124	1,125	139,500	9.3
HD 10 cm	40	640	175	78	22	815	113	89,270	5.95
HD 12.2 cm	30	720	175	80	20	895	150	134,250	8.95

*15,000 lbs/flight

Containers based on one year shipping maximum	Shipping containers per 1,600 tubes	Containers per pallet	Pallets
ISC 10 cm	267	28	10
ISC 12.2 cm	400	29	14
HD 10 cm	40	4	10
HD 12.2 cm	54	4	11

Individual Ice Core diameter	Weight per core	Individual container weight	Individual tube weight
10 cm	16	20	2.5
12.2 cm	24	20	3

outfitted prior to deployment, these MECC units should save valuable time at the drill site, likely 5 to 7 days of site set-up time, and the same from site pack-up time. These units would save time and facilitate a longer drill season, and consequently a shorter drilling project in the field.

With the large amount of ice core that will be extracted from Antarctica, either two to three MECC units (differing configurations) will be required to complete the core handling process in the field. These two to three units could have the following features:

1. A six-meter buffer room to handle excess core, when drilling outpaces core handling.

2. Attached directly to the buffer room will be the one-meter saw, “tray-up” and butyl evaporation roller racks.

3. Attached to that one-meter saw room is the butyl evaporation room. All three rooms will be supplied with refrigerated intake air, and will have exhaust fans to remove air that contains butyl vapor.

The core handling process breaks down as follows: lay down, move, cut, move, evaporate, move, store, individual pack, store, pallet pack, move, ship. In between are various coring and science measurements as needed

Head Core Handler Desk

A desk is needed for the head core handler. This is just five feet of table space, for a laptop and a place to keep some files.

SCIENCE REQUIREMENTS WITH RESPECT TO NECESSARY ONSITE INSPECTIONS

The following items are considered the minimum scientific information needed prior to shipping:

Coring information before cut

Measure raw core length to within 1 cm

Review core quality

Map fractures with sketches and digital photos

Determine orientation: inclination and azimuth

This information must be relayed to the drilling team as soon as practical for core quality assessment and so that any coring operational parameters adjustments as needed can be applied.

Coring information after cut

Measure detailed core length

Review core quality

Multiple measurements of depth

Comparison of records between core loggers’ and drillers’ active databases, to minimize error.

Core processing layout and issues

The core-processing layout is shown schematically in **Figure 21** at the end of this section.

Lay Down System

Core barrel must be moved to a horizontal position without bumping the core. An automatic system with continuously variable speed is preferred. A manually controlled continuously variable speed system is acceptable. A single-speed or step-speed system is not acceptable.

Drill fluid will flow from the barrel when it is lowered and must be collected and transported to a covered storage container.

Core Removal From Core Barrel

Non-brittle ice can be pushed from the core barrel, but movement vibrations must always be kept at a minimum. Brittle ice should not be pushed from the core barrel because the compression of the pushing may cause fracturing. Brittle ice, contained in a sleeve inside the core barrel, should be slid from the core barrel, using a hand or powered winch. The brittle ice should not be pulled or pushed out by hand because that could cause a stick-slip jerky motion.

The core inside the sleeve is slid onto a transport tray, used to move the core away from the drill. The transport tray can be a half cylinder, welded to an I-beam.

The transport tray and the drill barrel must be aligned along the same axis so the core does not have to “bend” to get out of the barrel and into the tray. The barrel must always be in exactly the same location. The alignment of the transport tray must be simply and precisely adjustable. There must be a system to check the alignment. A laser that is placed where the core barrel goes and a target that goes on the transport tray is a suggestion.

The transport tray must be kept at a temperature of less than -5ºC before the core is placed in it. If the transport tray is too warm it will melt the core. This means sometimes it will be necessary to hold the transport tray in the core logging area.

Fluid will continue to drip off the core when it is removed from the barrel and when first placed in the transport tray, and must also be collected and stored.

Core Transport

The transport tray is moved to the core logging area. Moving the transport tray along a roller track is a suggested method. The holding time of the core in the drilling area may not exceed the temperature dependent times mentioned just below.

Core Logging Area

The core logging area must be:

- Brightly lit so you can see what you are doing.
- Temperature controlled at about -15ºC: -12ºC is too warm for the ice, the loggers prefer it to not be much colder than -15ºC
- Fresh air inflow to blow off butyl fumes, such that it does not blow directly on core loggers.
- Not too noisy to work.

In some cases the last piece of core is laid down on the transport tray to match up the ends of the cores. This means the layout area is 1 meter longer than the longest drill run. The pieces of the core are assembled. The core is slid along the transport tray on plastic sheeting. Length of core run is measured to 1 mm.

Then the core is cut into 1-meter pieces and placed into transport trays. There will be saw slots in the transport tray to facilitate cutting without removing the core. Also needed is an ice core-cutting saw with minimal vibration. Each piece of the cut core (1 meter long) is placed in a uniquely numbered “core tray”. The number of trays needed for a season is dependent upon the expected coring interval.

Common data base parameters:

- Length of drilling run
- Length and depth of ice in each tray.
- What drill run went in what core tray.
- Core quality
- A sketch of the core
- The time at various steps of the operation
- The temperature of core logging area.
- Identity of the core handlers.

This information is entered into a computer at the core logging station with a backup system using paper and pencil, at least until confidence is established in the electronic database system. This database is networked with the drill information system and head core handler desk and computer.

The core trays are moved to an “evaporator” which may be integrated with the core cutting room. Hand moving of core trays can be minimized by using carts during this stage of the butyl evaporation process.

De-Butylizing Evaporator Building

Evaporation of the n-Butyl Acetate has always been a major factor in handling cores. De-butylizing evaporators are rooms are used to remove this drilling fluid from the core. Fresh air, with a temperature of at most -15ºC, is blown across the core. An active cooling system with fresh air inflow is required. There will be an ability to manually control the cooling system defrost cycles and fresh air circulation systems, to avoid the problem of blowing warm outside air into the evaporators during a defrost cycle. And there will be an automated temperature alarm system.

One of the more significant structures for the core handling train at Siple Dome was the initial core handling and debutylizing facility. It was a large structure with ventilation, refrigeration, core tables, ice saw, and various racks to store the ice cores while debutylizing. The schematic of this structure, shown in Figure G-1, was much more robust than needed, increasing mobilization time. This is an area for improvement.

After a cleaning with rags to get excess butyl off of the cores, a minimum of three days in the debutylizer was needed. In the debutylizer, a stream of cold clean air blew across the cores. This was more than sufficient to evaporate the butyl off of the outside of the cores; however, there has been discussion regarding the butyl that was either in fractures or between crystalline structures. The current methods of cleaning may not evaporate that butyl.

The size of the de-butylizing facility must be large enough to store maximum coring effort. In addition, the evaporator will be compartmentalized such that core that has been debutylizing for three days is not exposed to the vapors coming off of the core just laid down.

The evaporators are the most logistically intensive item in the core train, and need significant power for the cooling system.

After the core has been in the evaporators for three days the core is moved to the core storage tunnels. This requires moving the cores, in their core trays, down into a storage system using a core handling device (for example, an elevator in the case of a trench or tunnel storage complex). This could be another modular sled or dumb waiter that fits into the evaporator/core-logging complex. This surface complex should be taken apart and moved away from the drill area each winter to minimize drifting.

Core Storage Facility

Brittle ice must be stored on site over one or two winters. The storage facility has four functions:

- Store core (exposed, not packed into tubes)
- Provide a place to pack the core into tubes prior to shipment
- Provide a place to store the cores that have been packed and are ready for a flight out
- Science labs.

Tunnels are preferred over a covered trench because they are colder and the roof doesn't need to be removed afterwards. A covered trench is another option, but the logistics for a roof are large.

The storage facility must accomodate:

- All the brittle ice drilled in one year (+1,400 m)
- A core packing station
- ISC boxes (400 boxes), or new HD containers (54 containers)
- 1 to 3 science labs (6 x 12 feet)
- Space to move around.

The facility needs to be kept at a temperature less than –15ºC even when air circulates through. For below-surface facilities, the following will be considered:

- For temperature control, the facility top is at about 5 m depth.
- Narrow enough that the roof or overlying firn will not sag much while in use.
- Tunnels may need maintenance excavation, and this must not interfere with other activities.
- The preference is unsupported tunnels so roofing removal is not an issue.
- Wide enough to be have usable space.
- Well lit
- Emergency exits, at least at each end, not obstructed by snowdrifts
- Accommodation for dumb waiter
- Core Packing Station

When the core is transferred from the core tray to packing table, the following tasks remain:

- Lay out last piece of core and current 1 m piece of core from core tray
- An image is collected of each piece of core. This is a low-resolution image for documenting major fractures and ends. This is not a science-quality imaging system, which requires cutting the core.
- Measure core length (electronic and manual system)
- Tube number
- Core quality
- Names of core packers
- Date and time

- Manual sketch of core

After data are entered into a computer database system (with manual back up), core is packed into tubes, the tubes are packed in boxes, and the boxes are stacked on standard U.S. Air Force LC-130 pallets. Then the pallets are stored in a separate facility.

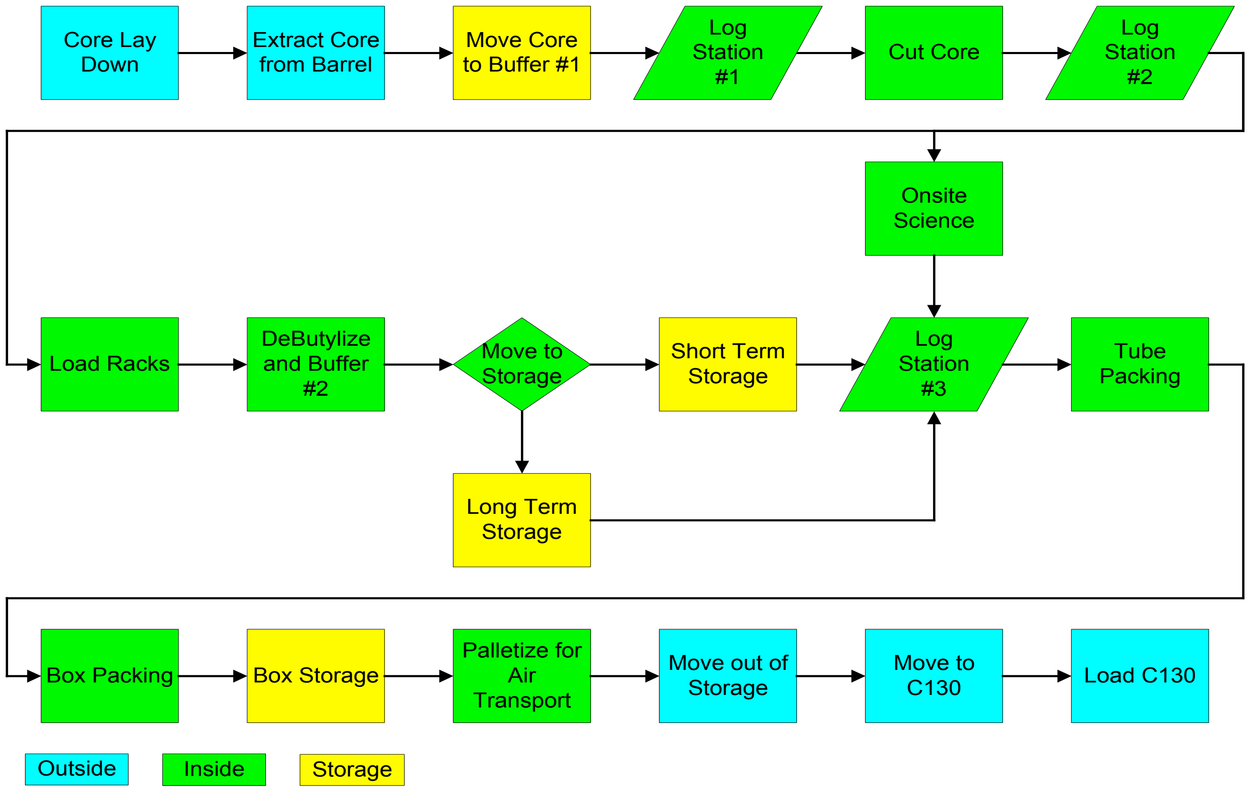


Figure 21: Field Ice Core Handling Train

TESTING PLAN

It is emphatically recommended that any deep ice coring drill be rigorously tested prior to mobilization to the field for science coring. Regardless of the option chosen, an extensive testing procedure must be implemented. This testing would include domestic testing of individual parts and with the system as a whole. Also included is a field test, suggested to be at the Greenland GISP2 site.

The domestic tests have the advantage of being relatively inexpensive to accomplish. There are many subsystems of any drill system that need testing and analysis. For example, testing should be accomplished on the chips and flow paths of the barrels and pump, core dog and catchers, different drill bits, instrumentation, and so on. In addition, the rig should be completely assembled in benign locations multiple times prior to its first mobilization. This will also allow the assemblers to determine and resolve building constrictions, assembly difficulties, and timing issues. In addition, such a test would indicate how to pack the drill for shipment.

The Greenland field test, proposed for the summer of 2005, would be a full-scale field test to rigorously check all aspects of drill operation and equipment. This test would be less expensive and would not compete for Antarctic logistics resources. It would also be an opportunity to train future US drillers and to run engineering experiments to solve potential coring problems (such as brittle ice recovery). This test would also be the opportunity to field test replicate coring equipment, techniques, and operations.

DOMESTIC TESTS

There are many component and system tests that can take place within the domestic United States. They include the following items.

Anti-torque types comparison tests

This will allow us to choose the best type and performance characteristics to suit the drill. Torque restraining abilities as well as the effect of anti-torque type on tripping rates can also be evaluated. There are a number of possibilities regarding anti-torque placement that can be determined with adequate cold room testing. The type of anti-torque design can determine how short we are able to make the drill. The shorter the drill string the easier it is to handle and operate, including directional drilling.

Cutter tests

Cutter geometry tests can be studied before committing to a specific design. This can have an effect on the design of the anti-torques as well. In the past, cutter geometries have tended to favor minimum power consumption. Brittle ice modeling may give insight into the possible ideal geometry for such conditions as brittle ice and basal ice containing sediment load. Carbide cutters may be desirable and would need to be performance tested.

Penetration shoe test

Various materials and geometries of penetration shoes need testing. Materials suitable for ice drilling may prove problematic for basal ice with sediment load. These materials can be tested for performance and wear and allow an adequate stock of spares to be produced that will complete the drilling objective without ordering excessive spares or running short of critical components.

Core dog and core catcher tests

A number of design options exist for refining the core dog geometry as well as looking at other types of core catchers that could improve drastically the core quality. Various configurations and/or types may be needed at specific depths to address the ice fabric characteristics. Besides the core dogs that have been used in the past, core catchers with multiple fingers could be tested for suitability. This information can then be used to determine the type best suited for producing science quality core. These designs will have an effect on the design to utilize an inner sleeve in the brittle ice zone to try and keep the core intact if fractured.

Chip path and flow test

A cold room test of the fluid path and performance characteristics of the screen, pump and core barrel assembly is essential. Fluid paths around the cutters and drill head are crucial to proper operation. The efficiency of the pump as well as the screen needs to be examined before a design commitment is made. Screen volumes and efficiency are important factors in the final drill design. Adequate chip volume must be designed into the drill to accommodate the chips produced during a coring run. This will allow sizing the screen accurately and help keep the drill as short as possible. This screen test will also allow a test of any gates or check valves designed into the system to enable the drill to e pumped in or out of the borehole. It would allow a test of a possible flow meter in the drill string to tell the status of the pump and screen while drilling.

Core barrel flexing characteristics

Tests can be performed on a completed core barrel assembly to determine the flex characteristics of various core barrel configurations. This will enable us to fine tune the design of drill handling components including the lay down table. This can help minimize the potential damage done to core in the handling process.

Cable load characteristics

The ability to accurately determine the depth of the borehole will require that load tests be done on the specific drill cable used. This load history will be imbedded in the drilling control software so that accurate depths can be produced utilizing the load history of the cable. This is a common industry practice and can easily be managed using the software of the drilling controls. This information will then be compared to the core handlers' depths and will be another bit of information that will be networked and combined with the rest of the drill run information. This data set will accompany the core. Also to be included in this series of tests would be cable termination tests. There are a number of cable terminations available that need to be reviewed for suitability. This test must be done in order that drilling software can be developed.

Depth measurement techniques

Accurate depth measurement is important for validating the actual amount of core recovered versus the indicated depth. This has been a recurring problem in the past. There are a number of types of depth measuring techniques that need to be tested to determine which is best suited for our core recovery process. Depth wheels with encoder readouts as well as magnetically tagged cables are but two of the options. This depth measurement option will be integrated into the drill cable load data and the instrumentation software to provide an accurate and repeatable depth reading.

Drill test to include instrumentation and data collection

A complete test of drilling controls and instrumentation must be conducted before deployment for the field tests. The control software must provide certain critical parameters in an easy to use interface for the driller. Many of the parameters need a range of adjustments as well as alarm thresholds. These important drill criteria must be incorporated into the development of a proper drilling procedure that can be easily incorporated into the driller training process. This will also influence the possible changes needed for the drill control software.

Drilling procedures

Drilling procedures and protocols must be developed before field-testing. A well-planned drilling procedure must be developed in conjunction with drilling training and instrumentation development. This must incorporate not only the drilling process but also data collection specifics and drill performance. This will ultimately lead to a drilling manual or document.

Cold Lab Materials Compatibility

Materials to be used in the field that have not been used previously should be tested in the before deployment to the field test. CRREL offers the best location for cold room tests because of their facilities and the well-stocked cold region-engineering library.

FIELD TESTING

Once the design is tested in a laboratory setting and the system is tested as an entire unit within the United States, it is imperative that a field season on the ice be initiated prior to actual science coring operations. The purpose of field-testing of any drill system is to test all components of the drill system that cannot be tested domestically. It is felt that a test season in Greenland may offer a cheaper alternative to Antarctic field testing and fit into the deployment schedule. This would allow test results to be interpreted and the design changes made in time for the Antarctic deployment. It would also allow the team to gain experience with the drill system so that it can be optimized from a safety, logistics and science perspective. And finally, it would allow the team to train the staff that will operate the drill in Antarctica

If this option were exercised it would require the permission of the Danish Research Board. The test should be done at a location that has similar surface and ice temperatures to the Inland site. GISP2 might be simpler because of the current hole and already have a presence there.

Test Objectives

A detailed set of tests and objectives will be developed during the design of the drill. The general objectives are to make sure the drill meets the science, logistics and operations requirements listed in other documents. These requirements place constraints on the quality of the core, the rate it is produced, the resources that are required, and health and safety issues.

Ideally the test would drill deep enough to get to brittle ice. At GISP2, this would require drilling to a depth of around 900 meters. At a minimum, the drill test must be deep enough to:

1) Demonstrate that the drill can produce high quality core

2) Learn enough about the various combinations of equipment and procedures so that well-informed decisions can be made on how to optimize the drilling process.

This will require coring at least 500 m and a third of this will likely have poor core quality. The test should also include collection of replicate cores.

Current thinking is that it will not be necessary to test the majority of the core handling equipment in Greenland. This equipment can be tested at NICL. If a cold test is necessary it can be done in the exam room. Most of the equipment that will be used at the Inland site can be tested in the NICL parking lot in the shelters that will be used for it at the Inland site. There may be a few pieces of equipment that should be tested in Greenland but they will have a negligible impact on the logistics. At least one person from NICL should be in the field during the drill test.

There are no science objectives for the test except for issues related to the engineering of the drill. There are opportunities for science associated with the test. These science opportunities should be proposed like any other science project, however they must not interfere with the testing of the drill.

Test Schedule

We will need to obtain permits from the Home Rule government. It makes sense to send some materials (like drilling fluid) to Greenland by ship.

In summer 2004 a surface casing, about 50 m deep, should be installed. This will give us a head start the following year and will require a two person drill crew. If we do the test at GISP2 and append a project to collect replicate core from the GISP2 hole, we will also want to run a caliper log in the GISP2 hole. This will measure the diameter of the hole, which is important to know for fabrication of the whipstock used in the deviation drilling. Buford Price could make the diameter measurements as part of a project he is proposing this February.

The drill test is proposed to be conducted in the Greenland summer of 2005.

Field Test Plan

Field tests will commence with the testing and set up of the drill system itself. Ease of set up and minimal logistics impacts can be noted and refined if necessary. The integration of camp logistics and drilling operations can be tested and modified. This will enable a well-refined, streamlined drill system to be developed for all future drilling.

The use of drilling fluids will require properly designed and well-fitted safety equipment. This safety gear must be compatible with all drilling related activities to provide a safe and efficient work site and must comply with the established safety plan. Modifications to this safety plan can be made before deployment to the actual WAIS drill site.

Drill instrumentation and controls must be rigorously tested in the field.

Driller training must be evaluated and can be adapted to comply with actual field situations encountered. The actual use of the drill will undoubtedly lead to modifications in technique and procedure.

Surface handling equipment and processes must be field tested to enhance speed in handling as well as protecting core quality. Assembly, alignment, efficiency and worker safety issues must be evaluated and modified if necessary.

Drill fluid recovery equipment tests will allow us to refine the actual drill fluid quantities needed to prevent over or under stocking of fluid supplies. The amount of fluid lost to evaporation and handling can be accurately determined.

The time it takes for the core to become free of drill fluid can be established and incorporated into any changes or modifications needed to streamline the core handling process.

Oriented core techniques can be evaluated and modified if necessary. It is essential that oriented core procedures not interfere drastically with drill and core handling processes and times. Field-testing will streamline this process.

Core recovery rates can be determined so that core-handling issues can be properly resolved. This will have an effect not only on drill handling and operation but also core handling issues including storage buffers and crew size.

Test fishing and retrieval equipment and techniques. Drilling operations will immediately cease if a foreign object has fallen down the borehole and cannot be recovered. A complete test of recovery techniques must be conducted to anticipate this unfortunate event.

A field test will allow a useful preventative maintenance plan to be developed based on actual operating parameters and field conditions. This will allow us to develop an adequate spares list including not only consumable drill components such as cutters and shoes but also major drill components critical for field operation. An adequate supply of drill components can be kept on hand without resorting to guesswork.

The field test will allow a real life test of camp and drill design criteria. Any unforeseen situations or conditions can be adequately addressed before an actual coring program commences.

Brittle ice testing

A variety of core dogs, core catcher types, cutters and penetration shoes should be tested. The issue of brittle ice recovery techniques must be analyzed and addressed.

The testing of various components performance in brittle ice cannot be adequately tested in the cold lab. It is difficult to produce brittle ice in the lab and will require a field test where brittle ice can be encountered. The tests that can be performed in the field regarding brittle ice are arguably the most important tests we can perform. All of the core barrel options as well as the core dogs; core catchers, penetration shoes, drill handling and core handling processes and procedures must be tested in actual brittle ice condition. The use of a core barrel inner sleeve in the brittle section of the core can and must be field-tested.

Tests regarding minimizing the thermal shock on retrieved cores can be conducted during the field test. There are several options available that could lead to improved core quality in the brittle ice zone.

REPLICATE CORING

Directional drilling is the art and science of deviating a borehole from vertical toward a predetermined target. Replicate coring would use many of the technologies developed for directional drilling in both the oil and mining industries and appears feasible. The desire to reuse the original cored borehole for logging in subsequent years means that the replicate coring tools must be retrieved from the borehole or, if left in the borehole, must allow access to the lower portion of the borehole. Consequently, subsequent runs in the original borehole must not be prevented by the sidetracks (the replicate core boreholes).

Bit Design

The bit design is critical to the directional characteristics of the EPICA/DISC. There are two factors that control borehole trajectory. They are bit tilt and side force. These two factors are affected by the bit type and thrust, rate of penetration, stabilizer placement and borehole clearance, bottom hole assembly stiffness and length, and ice characteristics. The interaction of these two effects dictates the direction of the bit force that in turn dictates the borehole trajectory.

Bit angle is the angle between a line perpendicular to the base of the bit and the centerline of the borehole (see **Figure 21**). This is the application angle of the bit force. The bit force is the load on the bit that generates the failure at the face of the bit. The bit tilt depends on the shape of the cutting structure, overall shape of the bit, and the assembly above the bit (to be discussed in the bottom hole assembly section). A short cutting structure will allow a larger bit tilt angle than a longer cutting structure, assuming the cutting structure is engaged in drilling. An analogy is a short versus long shovel. A short shovel is easier to manipulate than a long shovel. However, a short shovel will not dig as fast as a long shovel.

Similarly, a flat, short, even concave, overall bit shape will be easier to tilt than a long tapered overall shape. This is called a crown profile. A flat, short crown profile will have a smaller contact area along its sides allowing for pivoting to occur. A long tapered crown profile will have a larger side contact area, providing more stabilization.

The side cutting ability of a bit is related to the side force. If a bit is pushed into the side of the borehole, depending upon the crown profile and cutting structure, the bit will drill in the direction of the side force. This side force can be up or down, right or left.

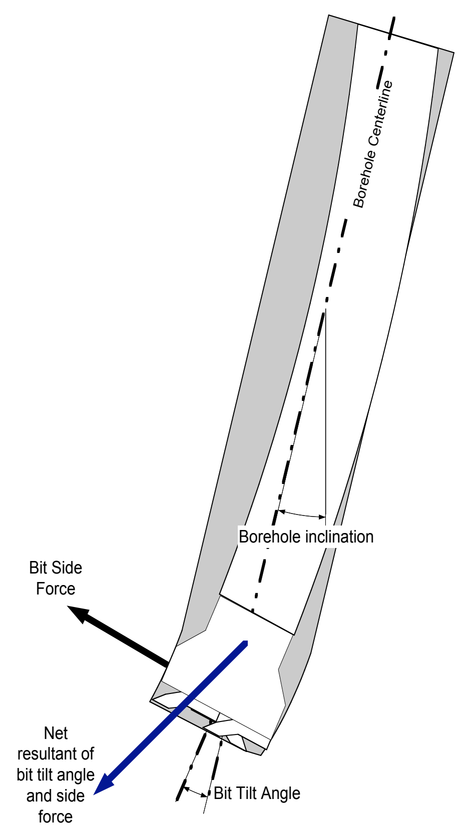


Figure 22: Bit Tilt and Side Force

The degree of bit tilt and side force dictates the magnitude of directional control. These bit tilt will have a major effect in hard formations while the side force will have a major effect in soft formations. If there is an uphole side force and uphole bit tilt, the wellbore trajectory will tend to build angle. Conversely, if there is a downhole side force and downhole bit tilt, the wellbore trajectory will tend to drop angle. If there is an uphole side force and downhole bit tilt, the wellbore will tend to drop angle in hard formations and build angle in soft formations. If there is a downhole side force and uphole bit tilt, the wellbore will tend to build angle in hard formations and drop angle in soft formations.

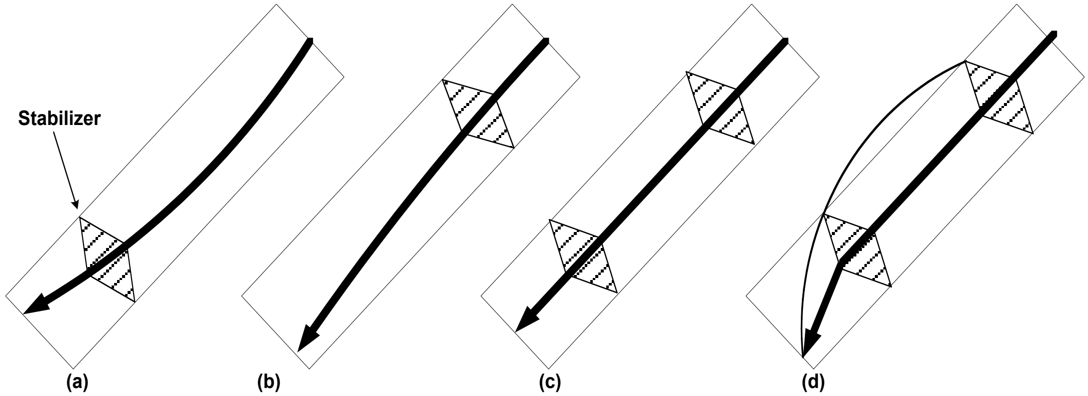


Figure 23: Stabilizer Placement Effects

Bottom Hole Assemblies

The bending of assembly above the bit influences borehole deviation tendencies [Hoffmann, 1912]

Stabilizers are placed in a BHA to control the direction of the entire assembly. The placement of stabilizers is based on fulcrums. A short stabilizer will tend to act as a pivot whereas a long stabilizer will tend to center an assembly. By judicious placement of the stabilizers, proper material and geometric properties of a BHA, and sound operational parameters, the driller can control the directional tendencies of a drilling assembly.

For example, by placing a short stabilizer near the bit as shown in **Figure 23(a)**, a BHA can be made to pivot about that point. This in turn, tilts and applies a side force at the bit. Depending upon the stiffness and orientation of the assembly above the stabilizer, the bit can be made to directionally drill in the desired direction. Since most strings tend to lie on the low side of the borehole, the bit tilt and side forces will tend toward the high side of the borehole. This type of assembly is typically used to build (increase) the inclination angle of a borehole.

On the other hand, if this same short stabilizer is placed further away from the bit as shown in **Figure 23 (b)**, the BHA will again pivot about that point. However, since the pivot point is further up the wellbore, the tilt and side forces will tend towards the low side of the borehole. This type of assembly, called a pendulum assembly, will tend to drop (decrease) the inclination angle of the borehole.

Should two or more stabilizers as shown in **Figure 23 (c and d)**, one near the bit and one further away from the bit be used, the assembly would not tend to pivot but rather be stiffer.

If the bit and these two stabilizers are collinear, this will tend to keep the wellbore straight. This kind of assembly is called a packed hole assembly. See **Figure 23(c)**. If the bit and the two stabilizers are not collinear, the assembly will describe an arc. This is called three-point geometry and is the basis of direction control in industry. See **Figure 23 (d)**. The assembly will drill an arc. The radius of the arc depends upon the distances from the bit and stabilizers and the degree of the angle the bit and stabilizers form as well as the ice and drilling operations parameters.(Cerkovnik, 1998) (Williams, 1998) (Schlecht, 1999)

The stabilization assumes that the stabilizers are in contact with the borehole walls. Often, the borehole is greater than the diameter of the bit that drilled it. This condition can cause great difficulty in maintaining trajectory control. Unless the stabilizers can be downhole adjustable, the contacts needed for pivoting or stiffening will not be available or worse, be far enough away to cause the bit tilt and/or side forces to not be predictable. Often this condition explains why bottom hole assemblies sometimes behave unpredictably.

General Bottom Hole Assembly Behavior

Millheim (1977) presented the following observations:

- All well paths exhibit an oscillatory behavior. This behavior is dependent on the bit thrust load, design, borehole size, formation type, and BHA configuration.
- Borehole curvature effects the prediction of the borehole trajectory and the application of bit thrust load.
- Initiating a build angle in soft to medium soft formations is more difficult than in harder formations. Once started, the borehole will build angle at either at steady state or accelerate.
- A change in BHA configuration may result in a transient "follow through" of the previous BHA directional tendency. This is attributable to borehole curvature.

Millheim made further observations in an eight part series of articles in the Oil and Gas Journal [1978a, 1978b, 1978c, 1978d, 1979a, 1979b, 1979c, 1979d]:

- The adjustment of bit thrust load provides some leverage for partial control of the bit side force. However, the higher the borehole inclination, the less the effect.
- An angle holding BHA is sensitive to borehole inclination. This is because the side forces exerted by the bit and BHA vary depending upon the formation being drilled. The "rules-of-thumb" for holding an angle are:
    - Make as few changes to drilling operating parameters as possible
    - Use the simplest BHA,
    - Make the angle holding section short.
- Very soft formations have the following effects:
    - It is easy to change trajectory with a flexible BHA.
    - It is difficult, maybe impossible, to change trajectory with a stiff BHA.
- Hardness variations are important to trajectory control.
- Penetration rate will affect the ability of a given BHA's directional tendencies.

Adding ice/bit interaction to BHA models complicates the problem. The eccentricity of the axial force (relative to the bit axis) to the bottom of the borehole, the lateral forces between the bit and the bottom and walls of the borehole, and the side cutting ability of the bit all affect borehole trajectories and are interrelated. (Ma and Azar, 1986) In Willamson and Lubinski's 1987 paper, the present the following statement:

> "The main limitation of using any computer model of BHA's is the reliability of input data. In particular, three parameters – hole curvature, dip angle, and stabilizer clearance – are difficult to obtain accurately and have as strong effect on the results."

POTENTIAL SOLUTIONS

There are two methods of sidetracking applicable to ice coring that are in industrial use today:

Blind Whipstock

Oriented Whipstock

Whipstocking is an old method of sidetracking a borehole. In this method a whipstock, which acts as a wedge to "direct" the bit, is placed in the borehole. This whipstock can either be placed so that the direction of the sidetrack is uncontrolled (blind) or the whipstock can be oriented so that the exit direction from the original borehole can be controlled (oriented). **Figure __** is a depiction of the whipstocking process.

A bridge plug, which blocks access from above to below that point, is placed in the borehole. The bridge plug has a set of slips that press against the sides of the borehole, preventing the plug from slipping down the hole. The bridge plug has an orienting guide, which assures the whipstock is pointed in the proper direction. The whipstock is then landed in the plug and the guide is then open to the drilling assembly. In this depiction the plug, whipstock and drilling assembly are run in one trip, but the processes can be broken up into separate trips. Normally, as depicted, the casing in the well must be milled through, then the hardened cement in the annulus outside the casing, and then finally the various formations need to be drilled through. Sidetracking an ice-cored borehole is simpler in that there is no well casing or cement sheath to penetrate prior to entering the ice. The ice is much softer and predictable than typical rock formations. This aids the process considerably.

There is one significantly important factor that is completely out of the realm of industrial directional drilling methods that occurs in ice coring. The standard bit used in ice coring pulls. One doesn't push it like every other bit. That is because ice core bits are related to augers. Every technique used in conventional directional drilling is predicated on the fact that one pushes a bit. How this will affect this operation is a serious unknown and is a large risk.

Because a standard ice core bit pulls, the entire BHA is put in tension. This has the effect of straightening the assembly. Normally, this would be good, as it tends to keep the borehole trajectory generally vertical with small variations. However, since the goal in replicate coring is to deliberately deviate the wellbore trajectory, this stiffening effect complicates the procedure. A bit redesign will be required that will allow the BHA to flex.

This redesign is also needed because as stated before, the primary means of directing the borehole trajectory is to either tilt the bit or apply a side force. A side force application is assumes that there are cutters on the side of the bit to cut into the borehole wall. In addition, side cutters are needed further up the BHA in order to ream the borehole for the BHA to transit. Current ice core BHA designs, with the exception of the KEMS 132 with its rotating outer barrel, are not suitable for this action as it is the internal barrel that is the bit driver. The outer barrel is stationary; cutters applied to the outer barrel will do nothing. Removing the outer barrel will disturb the fluid flow patterns and chip transport to the screen section would be disrupted.

Sidetracking an ice-cored borehole may be complicated by the need to core the exit hole and the relatively tight clearances between the coring assembly and the borehole itself. The greater the clearance, the easier sidetracking becomes. A major point of risk to deviating the borehole from the main borehole will be controlling the build gradient of the exit path. Experience has shown that build gradients of 3 to 5º/30 meters are relatively easy to handle, 10 to 20º/30 meters (or more) become more complicated and call for special techniques, such as articulated tools, knuckle joints and shorter, more flexible assemblies.

Another issue is the small clearances between the BHA and borehole. Given the a 6 mm clearance as exists on the EPICA drill, the sharpest turn that can be made is 1.36º/30 m, which gives a turn radius of 1,260 m. This is on the low borderline of achievable. This calculation is predicated on the assumption that the BHA lying on the low side of the borehole would form an even circular arc across its length. However, the EPICA probably has many varying stiffnesses throughout its assembly. How it would truly behave would require significant modeling or testing.

It may be possible to underream a hole. This is the process of running in with a tool that opens up downhole and reams out a section of hole to a larger diameter. This is how the Russians accomplished their sidetrack on their wells. They used a melter that opened a larger section of hole. They also used the thermal drill to drill away from the borehole 5G and into 5G-1 at Vostok. (Kudryashov et al. 2002) However, this would require a different bottom hole assembly. In addition, there is the added risk of the whipstock floundering in the borehole or the BHA catching on the lip of the borehole because the extra clearance would allow the BHA more room to move.

It may be that the EPICA/DISC drill will not be able to perform. In that case, a dedicated replicate coring assembly may be required. This unit could include articulated joints, kick sub to point the bit, and other dedicated design features just to directionally drill the replicate core hole.

The whipstock would have to be retrievable to allow the bottom of the original borehole to be accessed for future logging. The following methodology appears feasible to allow future logging. All boreholes will have some deviation. This deviation will cause tools to travel on the low side of the hole. If the well bore is sidetracked on the high side of the borehole, gravity will allow the successive logging tools to always maintain contact with the lowside of the borehole and avoid entering the successive sidetracks.

There are other industrial methods in use that may have applicability. But those processes are more mechanically complicated. If the whipstocking process has unknown problems in implementation, these other methods will be reviewed for potential solutions.

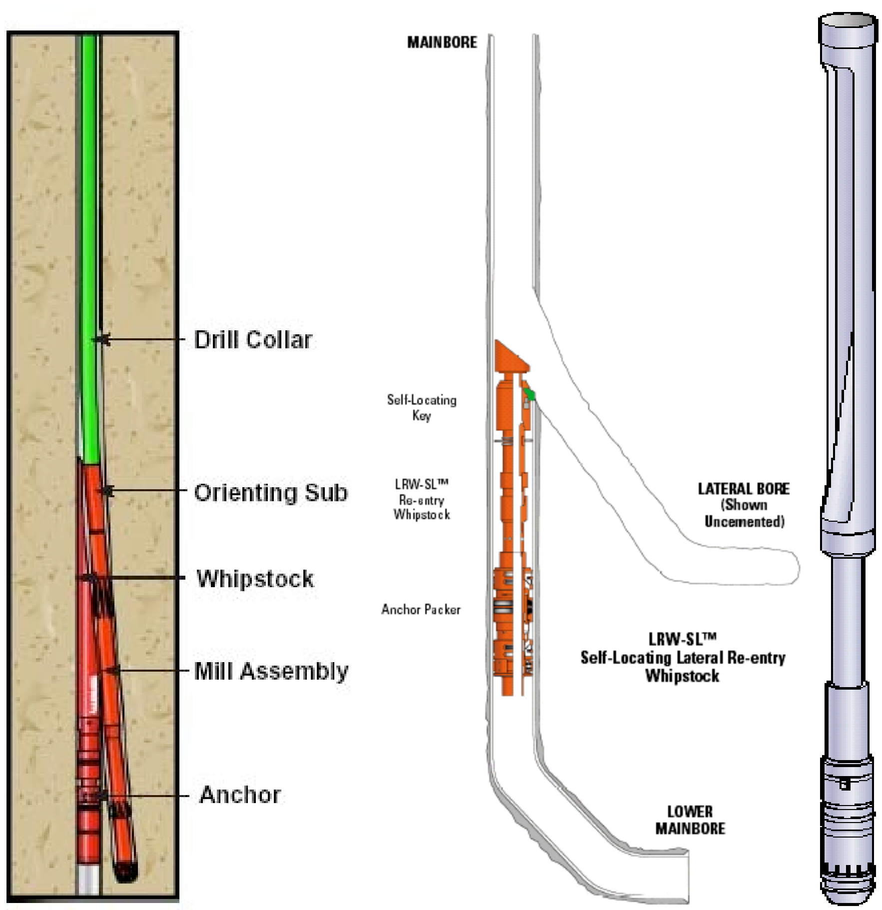


Figure 24: Whipstocking Process (from RMOTC and Halliburton web sites)

COMPARISON OF OPTIONS

EPICA OPTIONS

Three possibilities exist for use of a version of the EPICA drill for the US program:

EPICA drill with minimal modification

EPICA drill with some modification

EPICA drill with major modification

EPICA Drill with Minimum Modification

The EPICA drill could be built for use by the US program with a redesign of the BHA electronics. This redesign is necessary because of electronics in the existing versions of the drill are inadequate and obsolete. While some improvement in information and control may be achieved, the overall performance of the drill is unlikely to improve and the inherent problems with coring in warm ice, inability to core bed rock, and drill sensitivity would remain.

<u>Advantages</u> of this approach are as

Proven design

Excellent core quality

Light weight

Simplicity

Mechanically reliability

Titling tower facilitates core removal and cleaning

Little new design required if copied

Potential common sparing of some parts with Europeans

Potential increased collaboration with Europeans in further developing the drill; this may result in somewhat lower costs in the future

Trained drillers for the system may be available for US projects

<u>Disadvantages</u> include

Know problems in warm ice

Limited instrumentation and communications between BHA and surface

Ability to core bedrock is doubtful

Cannot be adapted for deviation drilling for replicate coring

Requires a highly skilled, experienced drill crew

The EPICA drill could be used with n-butyl acetate as the drilling fluid if that is deemed advisable. Changes to the drill itself would be limited to ensuring materials were compatible with the drilling fluid. Some additional design work would be required.

Risks associated with the minimal modification approach are that many of the currently defined science requirements will not be met. There is good chance, however, that with a properly trained crew, coring results would be similar to those achieved by the Europeans.

EPICA Drill with Moderate Modification

The basic configuration of the EPICA drill could be modified to overcome some of the drawbacks of current versions of the drill. As with the minimally modified drill, BHA electronics would be modified and, if necessary, components made compatible with n-butyl acetate. Changes made would be those that would improve safety and ease of operation without changing the basic configuration of the drill system. Change might include:

Drawworks – The drawworks would be "redesigned" to eliminate its tendency to fault.

Tilting Tower – Improvements would be made to allow powering up the motor to reverse the screw without bypassing safety switches. Features would also be incorporated to prevent the unplanned movement of the tower.

Control System – The control system would be redesigned to make the drill operate in a closed loop mode to improve performance and safety.

Cutter Head – The cutter head would be redesigned to improve somewhat the drill's performance in warm ice.

Flow Rate Measurement – Incorporating a flow meter in the BHA to measure the pump's volumetric flow rate would allow the drillers to determine the effect of changing drill speed on the pumping rate. This information may help improve drill operation.

<u>Advantages</u> of this option include those of the EPICA drill with minimum modification plus

Potentially better performance in warm ice than current versions of EPICA

Better control than with current versions of EPICA

<u>Disadvantages</u> of the moderately modified EPICA drill are

Performance in warm ice still somewhat problematic

Limited instrumentation and communications between BHA and surface

Ability to core bedrock is doubtful

Cannot be adapted for deviation drilling for replicate coring

Requires a highly skilled, experienced drill crew

Risks associated with this approach are that modifications cannot be made easily and that the modifications will only marginally improve drill performance. For example, if difficulties in warm ice are more a function of pump flow rate and/or chip flow channel size, drilling in warm ice might not be improved significantly. Deviation drilling and some other science requirements will probably not be met. However, it is highly probable that results at least as good as those achieved with the current versions of the EPICA drill would be achieved.

EPICA Drill with Major Modification

Major modifications to the EPICA drill might include all or some of the following:

Increasing size of the cable to allow faster data communication between the BHA and the surface. This would allow more and more frequent drilling data for logging and control purposes.

Increasing the size of the chip flow channel to improve chip transport.

Using a higher flow rate pump for better chip transport and “pumping” in and out of the hole to increase tripping speed.

Increasing the size of the core barrel and consequently of the outer barrel and the bore hole size.

Using separate drives for the drill rotation and pumping for better control and better performance.

Increasing core barrel length.

The major advantage of making these and other modifications to the EPICA drill is that there is a possibility of achieving more of the science requirements than possible with a closer imitation of the existing versions of the EPICA drill. The disadvantage is that each change moves the design away from the “known” attributes of the EPICA drill. This option taken to the extent of meeting all the science requirements possible becomes a totally new design. Depending upon what trade-offs are made between the science and other considerations (logistics, first costs, life cycle costs, etc.) the effort and risks become similar to those associated with the new DISC drill described in a following section.

DISC Options

The DISC drill would be tethered drill designed specifically to meet the science requirements developed and approved by the ICWG. Its design, fabrication, and operation would draw on the experience of the EPICA drill, the 5.2-inch drill, the Vostok KEMS-132 drill, and other drills as well as from methods commonly used in the oil and gas industry.

Two options for the DISC drill were considered for comparison purposes:

- 10.0 cm DISC drill capable of recovering core 10.0 cm in diameter
- 12.2 cm DISC drill capable of recovering core 12.2 cm in diameter

The fundamental design of the two drill systems would be exactly the same. However the larger drill would impact both the amount of science that can be done and the logistics required to support field operations. Advantages of either drill stem from the fact that they would be designed for the ICWG science requirements and would be the same:

- Modern instrumentation and control
- Designed core warm ice
- Designed to accommodate deviation drilling
- Not “locked into” a development path; i.e., it can take advantage of lessons learned from all previous drills
- More power available to better accommodate drilling into bedrock

- Improved "sparing" of components by using off-the-shelf parts where possible
- May be able to accommodate less experienced drillers

Disadvantages of the DISC drill are

- Increased risk in design, fabrication and operation since it is a new design
- Initially no drillers are trained in DISC system operation; i.e., everyone on steep portion of the learning curve
- Slightly higher logistics costs due to increased size of cable, power requirements, etc.

LOGISTICAL IMPACTS

The 12.2 cm DISC drill would require more logistical support due to the larger core size and borehole diameter. In addition, either DISC drill would, in principle, require more fuel than the EPICA because of their higher power requirements. Other logistical differences between the various drill systems are expected to be minimal.

Drilling Fluid

The EPICA drill produces a 13.0 cm diameter borehole. For a 3800 meter borehole the amount of drilling fluid to fill the hole would be approximately 13,400 gallons. Assuming that deviation drilling for replicated cores would result in 5 sidetracks of 150 meters each, an additional 2700 gallons of fluid would be required. If the total losses are 50%, the total amount of drilling fluid that must be transported to the drill site would be about 16,100 gallons. Total weight would be approximately 72,000 kg.

While not yet optimized for the DISC drill, the borehole produced by a 10.0cm DISC drill is expected to be approximately 15,3 cm in diameter. Assuming a 3800 meter borehole, approximately 18,700 gallons of fluid would be required to fill the hole. An additional 3,700 gallons would be required for 5 150-meter sidetracks. Total fluid, assuming 50% loss, is approximately 33,600 gallons. Total weight of n-butyl acetate would be approximately 100,300 kg.

The estimated size of the borehole for a 12.2 cm DISC drill is 18.1 cm. With the same hole depth and sidetracks, the total amount of drilling fluid would be approximately 47,100 gallons with a total weight of 140,600 kg. Of this amount, approximately 39,300 gallons would be required to fill the hole, 7,800 gallons for the sidetracks, and the remainder for losses.

During testing, it is expected that a borehole approximately 600 meters deep would be drilled. Assuming that testing of deviation drilling produced 3 75-meter sidetracks, total drilling fluid (including an 50% allowance for losses) for the EPICA drill, a 10.0 cm DISC drill, and a 12.2 cm DISC drill would be approximately 4,400 gallons (13,100 kg), 6,100 gallons (18,200 kg), and 8,500 gallons (25,000 kg) respectively.

Drilling fluid requirements are summarized in Table 4.

Core Transportation

A total of approximately 4500 1-meter tubes are expected to be transported from the drill site to NICL. The EPICA drill and the 10.0 cm DISC drill would require about 113 of the proposed HD containers. Total shipping weight would be approximately 33,200 kg and require about 6 flights.

The larger core produced by a 12.2 cm DISC drill is expected to require 150 HD containers and have a shipping weight of 50,100 kg. About 9 flights would be required.

Core transportation requirements are summarized in Table 4.

Table 4

Comparison of Logisitcal Impacts

Drilling Fluid	EPICA	10 cm DISC	12.2 DISC
Test – Volume (gal)	4400	6100	8500
Test – Shipping Weight (kg)	13,100	18,200	25,600
Test – Flights	2.1	3.0	4.1
Production – Volume (gal)	24,100	33,600	47,100
Production – Ship Wt. (kg)	72,000	100,300	140,600
Production -- Flights	11.8	16.4	23.0
Core			
HD Containers	113	113	150
Shipping Weight (kg)	33,200	33,200	50,100
Flights	6	6	9

Fuel Usage

The DISC drill system will require more power than the EPICA system and consequently higher fuel usage could be expected. Because the camp power system has not yet been defined (i.e., issues such as whether or not a generator would be dedicated to the drill have not been decided), the incremental impact on fuel usage has not been quantified.

COMPARISON OF ABILITY TO MEET SCIENCE REQUIREMENTS

Table 5 is a comparison of the various drill options' ability to meet the defined science requirements. It should be noted that while the existing EPICA drill's performance has been demonstrated, the DISC drill system's performance is predicated on what has been demonstrated with other drill systems, but not necessarily any single system. What combination of science requirements can be met effectively by a new design is not know. The "rating" for new design is, therefore, what is believed to be achievable for for the particular science requirement and trade-offs may be required.

Only three options are shown in the table. The performance of the 10.0 cm and 12.2 cm DISC drill system are expected to be the same. In addition, an EPICA drill with major modification is essentially a new drill design. The three options – 10.0 cm DISC drill, 12.2 DISC drill, and EPICA with major modification – are therefore considered to be the same for this comparison.

Comparison of Ice Coring Options for the Antarctic Inland Core Project

Table 5

Comparison of Options

		EPICA WITH MINOR MODIFICATION	EPICA WITH MODERATED MODIFICATION	DISC OR EPICA WITH MAJOR MODIFICATION	COMMENTS
Science Requirments					
1 General Requirments					
1.1	Ability to continuously collect core to a depth of 4000 m.	probable	probable	probable	
1.2	Ability to core in ice with 5% silt for a distance of 50 m.	difficult	difficult	probable	
1.3	Ability to drill in ice that is within 2^{o} C of the pressure melting point.	difficult	difficult	probable	Drilling rate in "warm ice" was very low at Dome C.
1.4	Ability to drill in ice that is within 2^{o} C of the pressure melting point without using antifreeze fluids. (This is desirable but may not be practical.)	difficult	difficult	probable	EPICA has drilled in warm ice using anti-freeze fluids
1.5	Ability to drill at borehole temperatures as low as –60 C, and surface temperatures as low as –40 C. (This is desirable; firm requirement is borehole temperatures as low as –40 C, and surface temperatures as low as –30 C.)	doubtful	doubtful	uncertain	
2 Core Characteristics					
2.1	Complete core recovery (100%) from top to bottom.	yes	yes	probable	
2.2	Ice pieces to fit snugly together without any gaps.	yes	yes	probable	
2.3	In non-brittle ice, the packed core should have no more than 12 pieces of ice per 10 meter section of core.				

		EPICA WITH MINOR MODIFICATION	EPICA WITH MODERATED MODIFICATION	DISC OR EPICA WITH MAJOR MODIFICATION	COMMENTS
2.4	In brittle ice there may be a lot of pieces in a single ~ 1m core segment, but the pieces must fit together and retain stratigraphic order. More than 80% of the ice volume must be in pieces that each have a volume > 2 liters.	yes	yes	probable	
2.5	Ability to determine the in situ orientation of core segments to within +- 10^{o}.	no	no	probable	
2.6	Core diameter to be > 98 mm. It is desirable that it does not vary by > 3 mm.	yes	yes	yes	
2.7	Core should not have any “healed fractures”, which cannot be seen but trap drilling fluid in the interior of the sample. “Healed fractures” probably form during drilling, then take up drilling fluid, and then later close off so they are not visible. The best way to avoid this is to not fracture the core.	uncertain	uncertain	uncertain	
2.8	Ability to know the drilling and core handling history of each core.	yes	yes	yes	
3	**Deviation Drilling**				
3.1	Ability to collect additional “duplicate” core that is at least 8 cm in diameter over an interval that is up to 150 m long and within 0.10 to 20 m of the main borehole. The purpose of this capability is to double (or triple) the volume of ice available for analysis in especially interesting depth intervals (for example, during rapid climate transitions, that typically occur over <10 m of core). Most duplicate cores will only be 30-40 m long.	doubtful	doubtful	uncertain	EPICA may be difficult to adapt for deviation drilling because of its basic configuration.
3.2	Ability to do this deviation drilling at specified depths and to do the deviation drilling at at least 5 depths.	doubtful	doubtful	uncertain	

		EPICA WITH MINOR MODIFICATION	EPICA WITH MODERATED MODIFICATION	DISC OR EPICA WITH MAJOR MODIFICATION	COMMENTS
3.3	The orientation of the deviation drilling is not important but needs to be known, and ideally should be less than 10 degrees off the main borehole.	doubtful	doubtful	uncertain	
4 Drilling Fluid					
4.1	Drill fluid to be evaporated from cores prior to packing so that it does not produce a hazardous vapor at NICL.	yes	yes	yes	Drilling fluid continues to be investigated.
4.2	Drill fluid to be immiscible with water.	yes	yes	yes	
4.3	Refractive index similar to ice (1.33 +/- 0.06) This is desirable.	unknown	unknown	unknown	
4.4	Drill fluid must not interfere with high-vacuum mass spectrometry (for example, silicone oil interferes with mass spectrometry and other analytical techniques for measuring trace and major constituents in the ice and gas phases).	unknown	unknown	unknown	
5 Hole Characteristics					
5.1	Hole diameter not to vary by more than 2% over 50 m, except for special conditions such as deviation drilling.	yes	yes	yes	
5.2	Hole inclination < 5 degrees from vertical.	yes	yes	yes	
5.3	Hole to remain open and accessible to the bottom for at least 10 years after drilling. The diameter during these 10 years must be at least 8 cm.	yes	yes	yes	

		EPICA WITH MINOR MODIFICATION	EPICA WITH MODERATED MODIFICATION	DISC OR EPICA WITH MAJOR MODIFICATION	COMMENTS
5.4	Hole wall to be smooth enough for optical logging. (Current thinking is that this means a surface roughness of < 0.3 mm plus removal of scars due to clamping marks. This is desirable but may not be practical.)	unknown	unknown	unknown	
5.5	Inclination, azimuth and diameter of the hole to be determined as a function of depth.	yes	yes	yes	
6 Depth Measurment					
6.1	Absolute depth measurement accuracy of 0.02% of depth.	yes	yes	yes	
6.2	Relative depth measurement accuracy while drilling of 2 cm over the length of the drilling run. (i.e. Ability to measure the length of core to within 2 cm while the drill run is underway.)	yes	yes	yes	
7 Drilling Information					
7.1	Recording of the following properties 10 times/second while drilling:				Limited bandwidth on drill cable will not allow data sampling and transmission at these rates with EPICA drill.
	Depth	no	no	probable	
	Drill rotation rate	no	no	probable	
	Cutting torque	no	no	probable	
	Weight on bit	no	no	probable	
	Penetration rate	no	no	probable	
	Fluid temperature	no	no	probable	
	Core barrel acceleration	no	no	probable	
	Measurement of core barrel flexing is desirable	no	no	probable	

Comparison of Ice Coring Options for the Antarctic Inland Core Project

		EPICA WITH MINOR MODIFICATION	EPICA WITH MODERATED MODIFICATION	DISC OR EPICA WITH MAJOR MODIFICATION	COMMENTS
8	**Bedrock Drilling Capabilities**				
8.1	Ability to collect up to 4 m of bedrock core at least 1.5 inch diameter in a frozen and non-frozen bed.	doubtful	uncertain	probable	
8.2	Ability to collect 2 m of unfrozen unconsolidated basal material.	doubtful	uncertain	probable	
8.3	Ability to drill 20 m of sandy ice (5% sand) and through 1 cm rock pebbles	difficult	uncertain	probable	
9	**Core Handling**				
9.1	Ability to electronically image every core segment. This imaging would be for curation and documentation of core quality. These images would not be suitable for statigraphic analysis, which would require considerably more effort.	yes	yes	yes	
9.2	Ability to measure the length of each core to within 1 mm.	yes	yes	yes	
9.3	Surface temperature of the core after removal from the drill.	yes	yes	yes	
	Core temperature never to exceed 0o C.	yes	yes	yes	
	Core temperature never to exceed -2o C for >2 minutes.	yes	yes	yes	
	Core temperature never to exceed -10o C for >20 minutes.	yes	yes	yes	
	Core temperature never to exceed -15o C for >1 hour.	yes	yes	yes	
9.4	Core segments (i.e. packed units of core ready for shipping) to have a length of 90 to 101 cm when packed in ~1 m long core tubes.	yes	yes	yes	

		EPICA WITH MINOR MODIFICATION	EPICA WITH MODERATED MODIFICATION	DISC OR EPICA WITH MAJOR MODIFICATION	COMMENTS
9.5	Ability to know the drilling and core handling history of each core segment.	yes	yes	yes	
Drill Performance					
	Maximum core length (m)	3	3	6	Targets for new drills
	Trip Speed (m/sec)	1.3	1.3	3	Targets for new drills
	Rate of Penetration (m/hr)	17.2	17.2	20	Targets for new drills

REFERENCES CITED

Arnason, B. Bjornsson, H. and Theodorsson, R. (1974) “Mechanical drill for deep coring in temperate ice.” J. Glaciol. 13 (67), 133-139.

Augustin, L. and Antonelli, A. (2002) “The EPICA deep drilling program.” Memoirs of National Institute of Polar Research, Special Issue No 56, 226-244, 2002.

Cerkovnik, J. (1998). Directional/MWD Seminar. Baker Hughes Inteq, Golden, CO.

Gundesstrup, N. and Talalay,P. (1994?). “Ice Coring Drilling Fluid Review”. Copenhagen, Denmark, University of Cophenhagen - Department of Geophysics.

Gundestrup, N. S., S. J. Johnsen, et al. “The EPICA deep ice core drill”. The Ocean and the Poles: Grand Challenges for European Cooperation. G. Hempel**:** 279-287.

Kelley, J. J. S., K.; Koci, B; Wumkes, M.; and Zagorodnov, V. (1994). “Ice coring and drilling technologies developed by the Polar Ice Coring Office.” Memoirs of National Institue of Polar Research (Spec. Issue, 49): 24-40.

Kuduryashov, B.B. et al. (2002) “Deep ice coring at Vostok Station (East Antarctica) by an electromechanical drill.” Memoirs of National Institute of Polar Research, Special Issue No 56, 91 – 102, 2002.

Ma, D. and Azar, J.J. (1986). “A Study of Rock-Bit Interaction and Wellbore Deviation”. Journal of Energy Resources Technology (September). 228-233.

McConnell, J.R., G.W. Lamorey, and M.A. Hutterli (2002). “A 250-year high-resolution record of Pb flux and crustal enrichment in central Greenland”, Geophysical Research Letters, 29(23), 2130, 2002b.

McConnell, J.R., G.W. Lamorey, S.W. Lambert, and K.C. Taylor (2002). “Continuous ice-core chemical analyses using inductively coupled plasma mass spectrometry”, Environmental Science & Technology, 36(1), 7-11, 2002a.

Mellor, M. and P. V. Sellmann (1974). “General considerations for drill system design”. Ice-core Drilling, University of Nebraska, Lincoln, NE, University of Nebraska Press.

Millheim, K.K. (1977). “The Effect of Hole Curvature on the Trajectory of a Borehole”. 52nd Annual Fall Technical Conference and Exhibition of the SPE, Denver, Co.

Millheim, K.K. (1978). “Here are the Basics of Bottom-Hole Assembly Mechanics”. Oil and Gas Journal, 98-106.

Millheim, K.K. (1978). “Operators Have Much to Learn About Directional Drilling”. Oil and Gas Journal, 62-64.

Millheim, K.K. (1978). “Proper Application of Directional Tools Key to Success”. Oil and Gas Journal, 156-165.

Millheim, K.K. (1979). “Behavior of Multiple-Stabilizer Bottom-Hole Assemblies.” Oil and Gas Journal, 59-64.

Millheim, K.K. (1979). “Control Techniques for Medium-Soft and Medium Formations.” Oil and Gas Journal, 178-186.

Millheim, K.K. (1979). “Controlling Hole Direction in Very Soft Formations.” Oil and Gas Journal, 106-108.

Millheim, K.K. (1979). “Hard-Formation Directional Drilling Calls for Special Care.” Oil and Gas Journal, 36-138.

Millheim, K.K., (1978). “Single-Stabilizer Behavior Described”. Oil and Gas Journal, 52-61.

Rothlisberger, R., M. Bigler, M.A. Hutterli, S. Sommer, H.G., Junghans, and D. Wagenbach (2000) “Technique for continuous high-resolution analysis of trace substances in firn and ice cores”. Environmental Science & Technology, 34, 338-342, 2000.

Schlecht, M., (1999). Directional Drilling, An Overview Seminar. Baker Hughes Inteq, Houston, Tx.

Ueda, H.T. (2002). “Some thoughts on deep core drilling system design.” Memoirs of National Institute of Polar Research, Special Issue No 56, 126-135, 2002.

Williams, J. (1998). Bottom Hole Assembly Design and Guidelines Seminar. Parker Drilling Company, American Association of Drilling Engineers Denver Chapter.

Williamson, J.S. and Lubinski, A., (1986). “Predicting Bottom-hole Assembly Performance”. SPE Paper Number 14764.

Zagorodnov, V.S., Thompson, L.G., Mosley-Thompson, E., Kelley, J.J. (2002). “Ice core drilling complications.” Memoirs of National Institute of Polar Research, Special Issue No 56, 196-205, 2002.

Appendix A

ANALYSIS OF HOW DRILL CHARACTERISTICS AFFECT THE TIME REQUIRED TO COMPLETE THE PROJECT

Kendrick Taylor and Will Fleckenstein independently using both deterministic and probabilistic methods, respectively, performed ice coring performance studies.

ICE CORING PERFORMANCE SPECIFICATION STUDY (FLECKENSTEIN)

The purpose of this modeling of ice coring is to determine the performance characteristics necessary to reach a depth of 3,800 meters within a prescribed number of time period of two Antarctic Field Sessions, and to look at the sensitivities of each of the system components. It is assumed that two seasons will consist of 50 days each season, or a total of 100 days, and includes the following activities:

Mobilization/Demobilization

Actual coring operations

Downtime due to equipment and personnel issues

Weather downtime

The base model incorporates trip speed, penetration rate, surface core handling time, core length, depth and unproductive time during which the coring rig is idled due to mechanical failure, weather, etc. The model mathematically expressed in its simplest form is (Gundestrup1994):

$$T(z) = \frac{(z - z_0)z}{3600/v_l} + \frac{(z - z_0)}{l}T_s + \frac{(z - z_0)}{v_m} + T^*$$

where:

$T(z)$ = estimate of total coring hours (hr)

z = total depth of well (m)

z_0 = initial depth (m)

l = average core recovery length (m)

v_l = trip speed (m/s)

T_s = surface time between core runs (hr)

V_m = rate of penetration (ROP) (m/s)

T^* = unproductive time

A sample calculation to estimate the time to core 3,800 meters of ice, assuming a trip speed (in/out) of 1 m/s, average core recovery length of 3 meters, surface time between runs of 30 minutes, an ROP of 20 m/hour, and 10 days of downtime results in a drilling time of 100 days. Obviously, if the drilling system meets these performance specifications, coring to 3,800 meters in two seasons is unachievable. The "technical limit", if all systems were reasonably optimized, if there were no core handling bottlenecks, and without downtime, is 24.5 days. This assumes a trip speed (in/out) of 2 m/s, average core recovery length of 6 meters, surface time between runs of 6 minutes, an ROP of 20 m/hour, and no downtime. The chances of achieving the goal of coring to 3,800 meters in 2 seasons increases as the properties of the fielded coring operation approach those of the "technical limit".

A Monte Carlo Simulation was utilized to determine the sensitivities of the final coring time to core length, trip time, and surface handling time, downtime and ROP. This is shown in **Figure A-1**. It should be noted that the simulation model does not account for interdependencies of variables. For instance, a longer core length will entail a longer coring assembly, which may or may not significantly impact the surface time between each run. It will be critical to quantify the interdependencies between variables during the design process, to ensure that one design parameter does not negatively affect several other portions of the design. It should also be noted that the Simulation model makes no attempt to estimate the effects of the design on downtime. Issues such as weatherization design, ease of mobilization, and logistical support are not considered as impacts on the time for each coring alternative. The table (**Table A-1**) quantifies the effect of each variable on coring time.

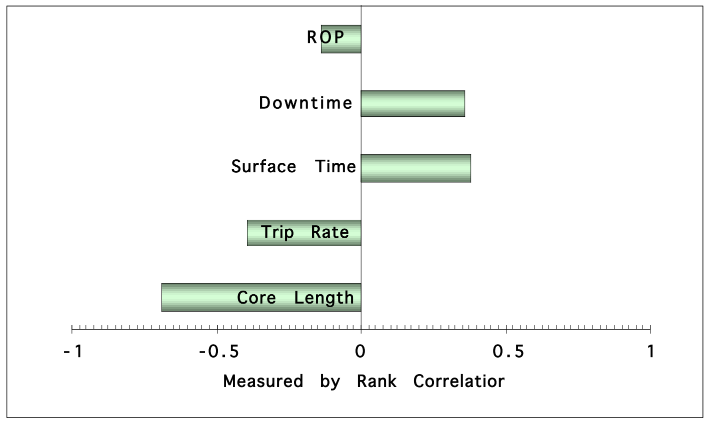


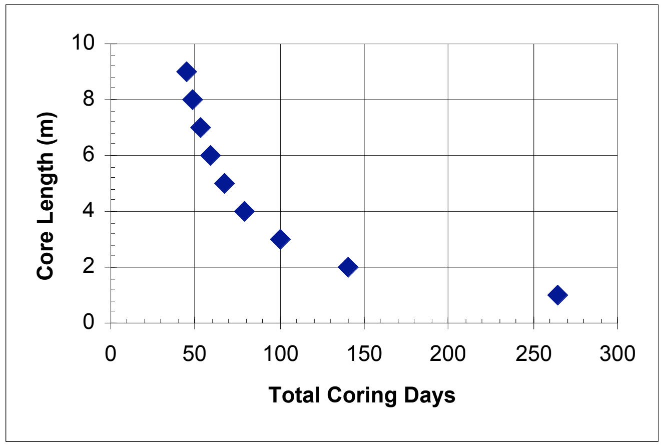
Figure A-1: Performance Sensitivity

CORE LENGTH

The variable with the most *apparent* effect on the coring operation and subsequent cost is effective core length. Effective core length has the largest correlation to total coring time, but is unfortunately the variable with the least control, since ice conditions, (brittle ice, primarily) decrease the effective core length, regardless of core barrel length design. Moving the effective core length from 3 meters to 6 meters shortens the coring operation by 41 days. In studying other industry coring operations, two methods are primarily used to maximize core length. First, give the drillers the option to go to longer core barrel lengths when the conditions allow for uncomplicated coring. Recovery of core lengths of 6, 9 even 12 meters in length may compensate for shorter core recoveries in difficult ice conditions. Also, the ability to attempt different methods of coring in troublesome medium (different core catching methods, core sleeving, inner core barrels of varying tolerances to the recovered core) may allow for longer runs. See **Figure A-2**.

The choice of an optimal core length in practice is difficult. Increasing the core length from 4 to 6 meters also greatly increases the length of the downhole coring assembly, negatively impacting the logistics and mobilization (due to the taller tower required at the surface), and also negatively effects the trip time due to greater fluid friction. A longer coring assembly may negatively impact the surface handling times also. The 6 meter core length at Siple Dome may have contributed to the operational difficulties due to a longer required tower, and additional complexity in the system needed to handle the longer core.

Figure A-2: Core Length Effect on Total



Regardless of the core barrel length chosen, it is critical that the actual core length recovered on each run is close to the core barrel length; in other words that the effective core recovered closely approximates the core barrel length. Experience has shown that existing technology used on the 5.2" coring system frequently allowed core lengths through the brittle ice zone of 1 meter. Core recoveries of 1 to 2 meters will significantly impact the chances of completing the core in 2 seasons. Further work will be needed on core recovery techniques in the brittle ice zone to achieve this goal.

TRIP SPEED

Trip speed, surface core handling and downtime have significant effects on the coring operation and fortunately are impacted the most by system design. See **Figure A-3**. Effort should be made to optimize these three factors, to provide the largest margin of safety in the event of unforeseen complications.

Trip speed up to approximately 2 m/s has a strong impact on coring time, saving 28 days over the base case of 1 m/s. Increasing the trip speed to 3 m/s would further save another 9 days. Speeds in excess of 3 m/s have diminishing returns. Speeds below 1 m/s negatively impact the coring operation and speeds below 0.5 m/s will prevent completion of the coring project in two seasons, regardless of other factors. Winch design, clearances between coring assembly and borehole, additional weight for tripping in the hole, pumping the coring assembly on trips in and out of the hole and fluid viscosity must be optimized to meet or exceed 2 m/s trip time, both in and out of the hole. It should be noted that trip speed is the portion of the design that we have the most control over. If other portions of the design do not meet

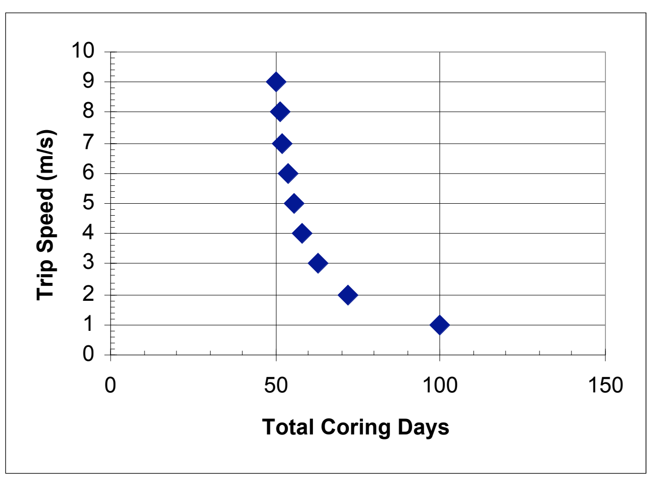


Figure A-3: Trip Speed Effect on Total Coring Days

expectations during field operations, such as effective core length, the importance of faster trip times increases.

SURFACE TIME

Surface core handling occurs out of the hole and is unaffected by downhole conditions. A study of offshore, deepwater drilling with similar high daily costs presents a possible solution. A dual drawworks system is utilized on those drilling rigs to allow the decoupling of surface handling and tripping operations. A similar design, using a multiple "rat holes", a duplicate coring assembly and a second, smaller winch to lower the coring assembly, service the core and reload, would get much of the surface handling off the critical path of tripping and coring. Achieving 6 minute turnaround times for the coring assembly at the surface would shave 21 days from the baseline case. See **Figure A-4**.

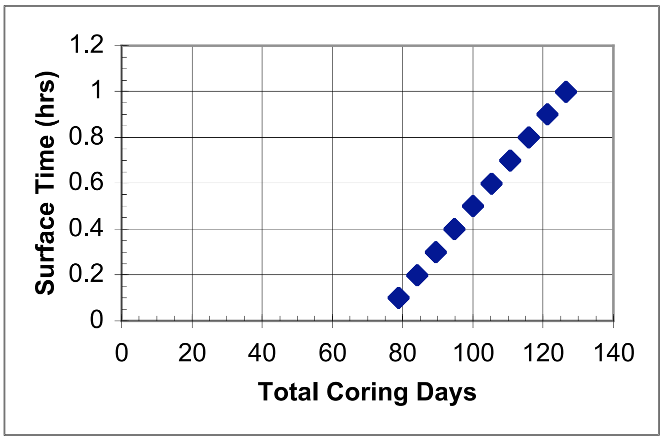


Figure A-4: Surface Time Effect on Total Coring Days

DOWNTIME

Controlling downtime is critical to meeting a schedule of 2 seasons for coring. See **Figure A-5**. Increasing the downtime from 10 days in the base case to 40 days loses 30 days. Redundancy and reliability of critical systems is a must. Use of dual downhole coring assemblies saves surface time, but more importantly provides insurance against a mission critical unforeseen failure of a non-field repairable part. A field test season is important to identify weaknesses and allow redesign of subpar performing systems. A field machine shop for onsite repairs will be critical, to avoid downtime due to offsite repair needs. System components must be chosen for ease of repairs and durability, with spares available for non-field repairable components. The system must be designed to allow simple, economical movements for operation, due to the nature of arctic operations, particularly if butyl is used as the drilling fluid. As much as practical, the operating area must be designed to minimize weather impacts, and the crews should be comfortable in the work environment, in all but the worst storms.

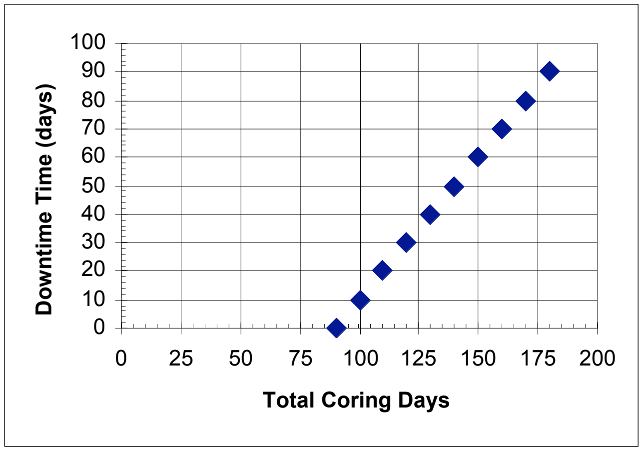


Figure A-5: Downtime Effect on Total Coring Days

RATE OF PENETRATION

See **Figure A-6** for the sensitivity of the total coring days to the ROP. Rate of Penetration (ROP) is not a significant factor if a minimum of 10 m/hr is achieved, but could be if the coring heads have significantly worse performance than in the past. Polycrystalline Diamond Cutter bits (PDC bits) and standard industrial diamond bits may be useful in not only retrieving rock cores and cores in silty ice, but also in coring ice. This is an area for investigation.

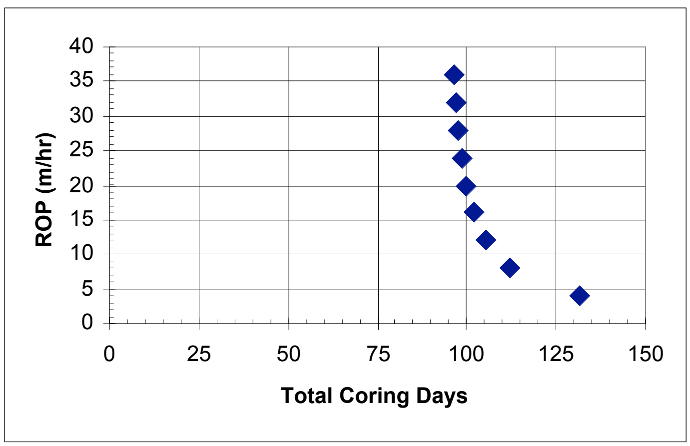


Figure A-6: Rate of Penetration Effect on Total Coring Days

OPERATIONAL PERFORMANCES

DISC

The optimal, reasonable design for the ice-coring rig to allow, 3,800 meters of core to be retrieved in 2 seasons should meet the following performance specifications:

Trip speed minimum:	2 m/s in and out of hole
Core length minimum:	4 meters
Surface turnaround maximum:	6 minutes

Rate of penetration average: 20 m/hr

Meeting these design performance specifications will allow the actual coring operations (which are defined as only the time to trip in, core the ice, trip out, and turnaround) to be completed in 33 days, making the rest of the two seasons available for mobilization/demobilization, weather related issues, logistics complication and other unforeseen factors.

EPICA

The EPICA system has the following operational characteristics:

Trip speed maximum: 1.4 m/s in and out of hole

Core length maximum: 3 meters

Surface turnaround average: 15 minutes

Rate of penetration average: 6 m/hr

Meeting these design performance specifications will allow the actual coring operations to be completed in 79.4 days assuming 24 hour a day operations. If the more normal 16 hour days of coring and 8 hours for conditioning the hole are used, the actual days coring is 119 days to reach 3,800 meters yielding a weekly rate of 225 meters of core which was the top performance of the EPICA drill at NGRIP. This will not accomplish the goal of 2 seasons to core.

Ice Coring Performance Specification Study (Taylor)

Taylor used a slightly different approach to calculate the time required to complete the project with different drilling systems. Taylor's approach calculates and sums the time required for each step of the drilling operation as the drill moves up and down the hole and the hole becomes progressively deeper.

For example, for each drilling run the time required for each of the following steps is calculated and summed to yield the total time required for one drilling run.

Lowering the drill through the casing.

Lowering the drill into the fluid.

Lowering the drill to the bottom of the hole.

Drilling the core.

Raising the drill to the top of the fluid.

Raising the drill to the surface.

Preparing the drill for the next drilling run.

The time required for each of these steps is a function the drill characteristics (i.e. how fast the drill can go up and down the hole, how efficient the drill system is in a particular operation) and the configuration of the borehole (i.e. the depth of the casing and fluid level and total depth of the borehole). The speed the drill is raised or lower is fastest when the drill is deep in the hole, slowest when the drill is leaving the fluid and the core in the drill is transitioning from being neutrally buoyant in the fluid to being fully supported by the core catchers, and is an intermediate speed when the drill is coming out of the hole.

After each drilling run the length of the core that was collected increases the depth of borehole. Then the time required for the next drilling run is calculated and added to the running total of time, and the length of the core that was collected increases the depth of the borehole again. This process is repeated until the bottom of the hole is at the bottom of the ice sheet.

The model allows the amount of non-productive time (i.e. routine maintenance, unexpected failures, weather delays and crew breaks) to be included. The model also allows the maximum depth that can be drilled in a single day to be specified so the result does not include a core production rate that would exceed the ability of the core handlers to process the core. The length of core collected each drilling run can be specified differently for ductile and brittle ice. This is done because shorter core lengths must be collected in brittle ice than in ductile ice.

The parameters in the model (**Table A-1**) can be adjusted to determine the expected performance of drills with different operation characteristics. The model was developed while drilling at Siple Dome and was used to adjust drilling procures so the coring was completed within the time window that was available. The model also predicts a production rate for the EPICA drill that is within 5% of the production rate of the EPICA drill at NGRIP.

Using this model it is possible to compare the time required to complete the Inland project using drills with different characteristics. A comparison of the EPICA drill as operated in cold ice at Dome C, and a range of possible operating parameters for the DISC drill is shown in Table kttable3. A major flaw in this analysis is the assumption that the EPICA system can drill as fast in warm ice as in cold ductile ice. Currently the EPICA drill has an extremely slow and impossible to predict production rate in warm ice. The model

Table A-1: Explanation of Taylor Model Performance Parameters

Model parameter	Explanation
Drill surface time (min)	The time required from when the drill comes out of the hole to when it can go back in the hole.
Speed in casing (m/min)	The speed the drill is raised and lowered when in the surface casing.
Fluid/air boundary speed (m/min)	The speed the drill is raised and lowered when it is entering and leaving the fluid.
Descent speed (m/min)	The speed the drill is lowered into the fluid filled portion of the hole.
Penetration rate (min/m)	The rate the drill penetrates the ice while coring.
Core length in ductile ice (m)	The length of the core that can be recovered in ductile ice. A 5.5 m long barrel is the longest length that will fit in an ISO shipping container.
Core length in moderately brittle ice (m)	The length of core that can be recovered on each drilling run in moderately brittle ice, this is expected to occur between 400 to 700 m and 900 to 1600 m.
Core length in very brittle ice (m)	The length of the core that can be recovered on each drilling run in very brittle ice, this is expected to occur between 700 m and 900 m.
Ascent speed (m/min)	The speed the drill is raised in the fluid filled portion of the hole.
Ice thickness (m)	The total amount of ice that has to be drilled.
Number of hours per day when drilling is occurring (hours)	This does not include the time required for daily maintenance that cannot be preformed while drilling and minor problems.
Number of days between days when no drilling occurs (days)	Drilling does not occur on some days because of storms, holidays, or crew fatigue.
Maximum number of cores per day (m)	The maximum meters of ice the core handlers can handle in one day.
Number of days to set up drill each season	How long it takes from when the drillers arrive on site to when the drill is operational.
Number of days required to complete project (days)	Output of model. Total number of days required for drilling. Does not include time to setup drill, ramp up operations, and shutdown drill at end of season.
Number of seasons to complete drilling	Output of model. Number of seasons required to complete the Inland project drilling. Each season requires time to set up equipment which depends on the drill system, 7 days to ramp up operations, and 5 days to shut down. Each season is considered to be 55 days long. This allows 15 days/season for drilling and logistics contingencies. Total time available for all drilling operations is expected to be 70 days. This also includes one season to establish the camp and set the surface casing, and one

predictions of the EPICA drill production rate in warm ice are not consistent with reality. There is no way to determine how long it would take the EPICA drill system to drill through the warm ice of the Inland site and it is possible that EPICA drill system would never be able to complete the task. The predicted performance for the EPICA drill is for a hypothetical EPICA drill that has been modified to work effectively in warm ice. In practice the EPICA program has been unable to make such a drill. If modifications cannot be made to the EPICA drill to enable it to drill in warm ice, the time required to complete the Inland project with the EPICA drill would be infinite.

Table A-2 is the predicted time required to complete the Inland project with different drill configurations. The EPICA drill used in the model is assumed to be modified in such a way that it can efficiently drill warm ice. In practice such a drill does not exist and may not be possible to construct. DISC1 to DISC5 are performance characteristics for different possible designs of the DISC drill. Model input values that are different from the previous column are in bold font and are followed by an ktfit1: Possible cut plans for cores of different diamet

Table A-2: Taylor Model Performance

Model parameter	Modified EPICA	DISC1	DISC2	DISC3	DISC4	DISC5
Drill surface time (m)	15	**10 ***	10	10	10	10
Speed in casing (m/min)	10	10	10	10	10	10
Fluid/air boundary speed (m/min)	5	5	5	5	5	5
Descent speed (m/min)	70	**100 ***	100	100	100	**120 ***
Penetration rate (min/m)	10	10	1.5	1.5	10	10
Core length in ductile ice (m)	3	**5.5 ***	1.5	1.5	5.5	5.5
Core length in moderately brittle ice (m)	2	2	1.5	1.5	2	**4 ***
Core length in very brittle ice (m)	1.5	1.5	1.5	1.5	1.5	**2 ***
Ascent speed (m/min)	90	**100 ***	100	100	**120 ***	120
Ice thickness (m)	3800	3800	3800	3800	3800	3800
Number of hours per day when drilling is occurring (hours)	20	20	20	20	20	20
Number of days between days when no drilling occurs (days)	9	9	9	9	9	9
Maximum number of meters cored per day (m)	80	80	**50 ***	**40 ***	**50 ***	50
Number of days to set up drill each season	12	**7 ***	7	7	7	7
Number of days required to complete project	107	66	69	79	68	66
Number of seasons required to complete drilling (This includes 1 season to set up camp and surface casing, and 1 season for replicate coring. It does not include a season to remove the camp.)	6 or 5.5	4 or 3.8	4 or 3.9	5 or 4.1	4 or 3.9	4 or 3.8

* Indicates this value is different than the previous column.

Figure A-7 Possible cut plans for cores of different diameters

APPENDIX B

RUSSIAN KEMS-132 ELECTROMECHANICAL DRILL

HISTORY OF THE KEMS-132 ELECTROMECHANICALDRILL

Most of the Vostok borehole has been electro-thermally drilled. Initially progress was made to 2500 meters employing a thermal drill. Subsequently, the drill (TBZS-152) became stuck above the bottom at 2250 meters, and the cable was intentionally broken off. A kick-off was then made 50 meters above the stuck drill, at 2200 meters. The thermally deviated borehole was then continued, using thermal drilling, to a depth of 2755 meters.

The Russian KEMS-132 Electromechanical Drill was deployed at Vostok during the 40th Russian Antarctic Expedition (RAE), 1995, to extend the deviated borehole beyond 2755 meters. During the next three (and somewhat shortened) Antarctic seasons, electromechanical drilling has progressed to a depth of 3623 meters using the KEMS-132 drill.

Features of the KEMS-132 Electromechanical Drill

The following are the major features of the KEMS-132 drill:

- Bottom Hole Assembly (BHA) Weight: 240 kg (530 lbm.)
- BHA Length: 8-13 meters (26- 43 ft.)
- Outer Diameter of Drill Head: 135 mm (5.31 inches) OD
- Inner Diameter of Drill Head: 106 mm (4.17 inches) OD
- Core Barrel Length: 3 meters (10 feet)
- Bore Hole Diameter: 135 mm (5.31 inches)
- Normal Drill Rotation Speed: 90-220 rpm
- Motor voltage: 220V AC, 50 Hz, three-phase
- Motor rotation speed: 2800rpm
- Penetration rate in ice (max): 20m/hr
- Penetration rate in rock (max): 1.5m/hr

- Average core retrieval length: 2.8m
- Teflon coating used on drill head allows drilling in warm ice (-10C)
- Maximum bore hole depth: 4000m
- Average tripping speed: 0.7m/s
- Cable-Diameter: 16mm (.63 inches) OD
- Cable-Breaking strength: 97 kN
- Cable-Number of conductors: 8
- Cable-Specific resistance of one conductor: 9 ohms/km
- Height of tower: 15 m (49 ft.)
- Power Generator: 20 kW
- Power consumption-Draw works motor: 20 kW
- Power consumption-Heating system: 12 kW
- Power consumption-Lights: 5 kW
- Drill operating temperature (minimum): -60 C
- Drill external operating pressure (maximum): 40 MPa (5,700 psi.)

KEMS-132 Electromechanical Drill configuration:

- Pump is a separate motorized pump
- Pump is positive displacement
- Pump is pumping clear fluid
- Outer rotating barrel
- No core barrel
- Drills warn ice
- Extract core vertically
- Cutter shoes positioned as far from the cutting edges as practical
- Drills sub-glacial rock

- Near-bottom circulation of fluid
- Optimized cutter and cutter head geometry for warm ice
- Deviation drilling potential