DEVELOPMENT OF THE U.S. DEEP CORING ICE DRILL

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Abstract: The United States has developed a deep coring ice drill capable of retrieving 13.2 cm diameter cores 6 m long. A comprehensive discussion of the developmental factors surrounding the design, fabrication and refinement of the United States 13.2 cm deep coring ice drill is presented. Included in this paper are the various design param which defined the final configuration and approach. Technical theories and their affect on drill design are discussed. New drilling fluids for use in deep bore holes have been developed for increased safety and health benefits which impart additional problems on the synthesis of deep coring drill designs. Drill handling design problems as well as safety and environmental concerns are presented. Design evolution and modifications are discussed in detail.

1. Introduction

Since approximately 1986, the United States has been actively developing the capability to recover continuous ice cores to bedrock in a fluid filled bore hole. In the course of developing this capability, a number of design approaches were modified to enable the ice core scientific community to adequately address critical issues related to both scientific sampling protocol and deep drill development.

The last deep ice coring effort with U.S. involvement was the GISP1 program which produced a 2037 m core to near bedrock near Dye 3 in South Greenland (65°11'N, 43°49'W; h=2490 m asl). The drill used to recover this core was a version of the ISTUK system developed and built by the Geophysical Isotope Laboratory, University of Copenhagen (GUNDESTRUP *et al.*, 1984). It is designed to work in a fluid filled bore hole and is capable of retrieving a 102.3 mm diameter core in lengths up to 2.75 m. It produces a bore hole with a diameter of 129.5 mm. The drilling fluid used was a mixture of kerosene (Jet A1) and perchlorethylene (PCE).

In 1986, the Polar Research Board published the report *Recommendations for a U.S. Ice Coring Program* (WEERTMANN, 1986). This report addressed current U.S. coring capabilities and made recommendations regarding the action plan for achieving the desired ice core drilling and ice core analysis capabilities for future national and international science plan strategies. The U.S. Ice Core Research Workshop, held at the University of New Hampshire in June, 1988, further defined the need and character of future ice core drilling efforts (MAYEWSKI, 1988).

Evolution of developing the U.S. deep drilling capability brought out the need to re-address several design constraints. Recent technological advances have re-structured the scientific strategy to accommodate analytical protocol that required higher sampling densities and address the needs of increased investigator participation. Thus the need for a larger diameter core.

The diameter finally decided upon was 13.2 cm. For project efficiency, the core retrieval length was also re-defined as being 6 m. These requirements manifested themselves as design challenges that were developed and refined during the GISP2 deep coring program (KOCI, 1989). This paper provides an over view of how these design elements evolved as they pertain to the deep drill itself.

2. System Description

The drill used for core recovery for the Greenland Ice Sheet Program 2 (GISP2) is designed to operate in a fluid filled bore hole to a depth of 3300 m. It's goal is to produce a continuous ice core to bedrock and also have the capability to retrieve sub-glacial samples.

The diameter of the ice core was defined as 13.2 cm. Operationally it was desired to have a recoverable core length of up to 6 m to minimize the number of coring runs necessary. This required reconsideration of the drill handling techniques that had been implemented in the design of the shallow and intermediate coring drills (Fig. 1).

After considerable discussion regarding the controversial use of polybrominated biphenyl ethers (PBBE's) as drilling fluids, an exhaustive search revealed several options that would minimize both health and environmental concerns. The drilling fluid chosen as a result of this investigation was n-butyl acetate (GOSINK *et al.*, 1991). The use of this type drilling fluid placed additional design considerations on the development of the deep coring drill.

The drill needed to address the requirement for handling the chips that were produced during the coring process as well as the method by which long large diameter cores were handled at the surface.

The drill string is suspended by an electromechanical cable which is capable of maintaining a communications link between the down hole portion of the drill and the drill control located at the surface. The entire system must be assembled and disassembled in the field and possess the ability to be air transported to the drill site by ski equipped LC-130 Hercules aircraft.

All drill operations are controlled and monitored from the surface (HANCOCK, 1994). Power for the drill is transmitted down an instrumented cable which utilizes a Kevlar strength member. Variable AC power of 0–1100 V is supplied to the drill by way of a slip ring mounted at the winch as well as a down hole slip ring that will supply the drill power requirements should the drill spin in the bore hole. Power from the surface enters the transformer section where it is stepped down and rectified to produce the 0–120 V DC that the drill motor requires. This power is in turn fed through the instrument package where the forward/reverse and run/stop relays are located. This method of powering the drill offers several advantages. All power control can be applied from the surface with a minimum of input from the instrument package. This provides a run forward default situation should the instrument package fail completely while down hole (HANCOCK and KOCI, 1989).

The power is fed to the motor section of the drill through special butyl acetate- proof high pressure feed-through connectors. The motor section consists of a 2.2 kW DC motor and 17:1 ratio circulute gear reducer to reduce the speed to 0–150 rpm. The drive shafts
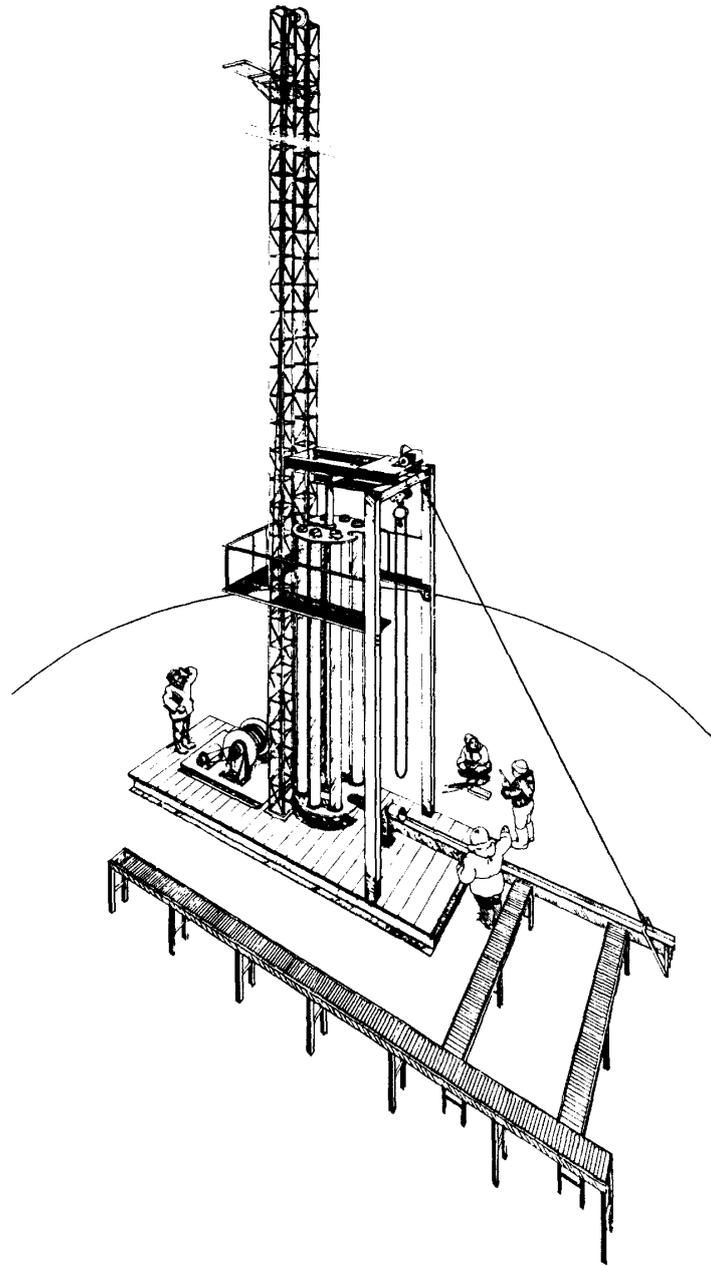
Fig. 1.   Drill handling configuration of the PICO 13.2 cm deep coring ice drill.

running through the screen section(s) transmit this power without interfering with the chip collection in the screens. The output of the pump rotor shaft in turn drives the inner core barrel and head assembly. As the drill motor is running, the pump and inner core barrel assembly are turning. The intake of the pump is connected to the annulus between the inner and outer core barrels.

The chips produced in the cutting process are pumped up through this annulus and into the screen sections located immediately above the pump. The chips are confined in the screen and the drilling fluid returned to the bore hole.

The core barrel assembly consists of an inner and outer core barrel. The inner core

barrel rotates and has the coring head mounted to it. The outer core barrel does not rotate and serves to center the inner core barrel in the bore hole as well as providing the annulus by which chips are pumped into the screen section.

The coring head is attached to the rotating inner core barrel and consists of three razor sharp cutters whose depth of cut is limited by a penetration shoe. As the core barrel rotates, these cutters remove an annulus of cuttings and the inner core barrel straddles the core as the barrel progresses downward. When the core barrel is nearly full the rotation is stopped. Located in the head are three spring loaded core dogs which engage with the ice core as the drill is withdrawn. These cause stress concentrations at the three points of core dog contact and the core is broken. The core dogs also retain the core in the core barrel for the trip to the surface.

2.1. Drill cable

The drill cable used with the GISP2 drill had to meet a number of design constraints. Total length needed to be in excess of the maximum expected depth which, for the GISP2 drill site, was determined to be 2975 +/– 235 m (HODGE et al., 1990). The drill cable design reflected the need to operate in n-butyl acetate without detrimental effects. The cable must be capable of supplying the power requirements of the coring process as well as provide a clear communication link between the down hole drill microprocessor and the drill control microprocessor located at the surface. A final and critical requirement was that the cable must be air transportable to the drill site in central Greenland by LC-130 aircraft.

The cable designed for GISP2 was specified to be 4200 m in length. The tensile strength was defined as 20000 pounds. This strength would accommodate the combined drill weight and core breaks for the given core diameter. Because of weight restrictions involved with deploying the drill cable to the drill site, steel was eliminated as a viable option. This left synthetic fibers as options for the drill cable strength member. After evaluation of the various synthetic fibers available, it was decided that a Kevlar strength member would serve the need for a fiber that possessed the strength required for drilling and making core breaks as well as being impervious to attack by butyl acetate.

The completed cable had a diameter of .810 inches and was 4100 m long after a 100 m section was removed to allow testing to enable the winch manufacturer to properly design the cable spooling mechanism. The cable weighs 3200 pounds in air and 900 pounds immersed in butyl acetate.

The cable is made up of 4 signal wires in the center of the cable. These are 20 gauge conductors with Teflon insulation which is impervious to attack by butyl acetate and petroleum distillates. It is surrounded by a Mylar foil shielding and incorporates a 22 gauge braided drain wire. This is in turn surrounded by a woven Dacron protective jacket. Around this bundle are placed the power conductors which are 18 gauge wire with Teflon insulation. All conductors used for the construction of the drill cable are individually spark tested to 3000 V before being incorporated into the cable.

A Kevlar strength member is woven in two opposing layers around the central conductor bundle. This Kevlar strength member has a tensile strength rating of 20000 pounds which must not affect the performance of the conductors under these loads.

2.2. Winch

The winch necessary to handle a drill cable of this length and type must address specific requirements. No stock winches existed that could accommodate these specific needs. The winch is of the standard drum type. It has specially designed grooves machined on the winch drum to facilitate effective cable spooling and increase cable life. It is hydraulically driven with a four cylinder hydraulic motor. Hydraulic power is provided by a prime mover which is a diesel engine driving a hydraulic pump. The pump is a variable pressure/variable volume pump that controls winch speed and torque. It is operated from the drill control room by a remote control panel. All critical winch functions are monitored and controlled remotely by the drill operator.

The prime mover providing hydraulic power is a separate unit that can be located up to 50 m away from the winch. It is powered by a Detroit Diesel 4-71N with a hydraulic governor set at 70 horsepower and 1800 rpm. It is designed to run at an altitude of up to 3800 m asl and has a temperature operating range down to −40°C. The winch specifications were originally stated as a maximum speed of 150 m per min and slow speed capability of .5 m per minute. Experience has proven that maximum speeds of approximately 30–40 m per minute were desirable due to the drill string/bore hole clearance and drilling fluid viscosity. Slow speed operating characteristics proved to be the most critical aspect in winch design and implementation. The accurate drilling of ice cores requires an even and infinitely adjustable and repeatable slow speed cable feed. This slow speed feed has the greatest effect on core quality and bore hole geometry. If the weight on the bit can not be adequately controlled so as to keep the cutting rate in line with penetration rate, the result will be bore hole deviation and poor core quality. Several design modifications were made to optimize the slow speed penetration performance.

2.3. Anti-torques

The anti-torque section of the drill is necessary to prevent rotation of the upper portion of the drill string during the drilling process (Fig. 2). It must develop enough torque restraining capacity to prevent the upper drill section from rotating in the bore hole as well as allow freedom of vertical movement in and out of the bore hole.

The anti-torque system consists of two sets of anti-torque leaf springs each containing 6 leaves. The anti-torque springs are in the shape of a 4th order parabola. They were designed based on calculations described by N. REEH (1984). This produces a spring shape that offers the most efficient and uniform loading on the bore hole wall. The springs are mounted on sliders which are adjustable to allow the springs to accommodate varying bore hole diam.

Initial design incorporated pre-bent anti-torque springs. The springs were made of 316 stainless steel alloy. Use of this type of anti-torque proved it to be lacking the necessary torque restraining capabilities which caused the drill to spin. In 1991 the 4th order parabolic springs were built incorporating a number of additional attachments and adjustments that would enhance the torque restraining capabilities under various conditions. It was found that the parabolic springs worked so well that full load motor current could be restrained by these anti-torques while allowing free movement up and down the bore hole. Additional sets of anti-torque springs can easily be added to the drill string to withstand the additional torque requirements of taking sub-glacial samples.

2.4. Transformer section

The transformer section serves the function of stepping down and rectifying the power transmitted down the drill cable (HANCOCK, 1994). At the surface is a high voltage transformer which takes the 0–240 V surface supply and steps it up to 0–1100 VAC. This simplifies power transmission and drill motor control. It allows a run/forward default capability should the instrument package develop problems down hole. This has proved useful on several occasions during the drilling process.

The transformer section takes the incoming 0–1100 VAC from the surface and steps it down and rectifies it to the 0–120 VDC that is required by the drill motor section. This power is supplied to the motor section by way of run/stop and forward/reverse relays and high pressure electrical feed-throughs. All drill motor relays are controlled from the surface and executed by the instrument package.

2.5. Instrument section

The instrumentation incorporated in the deep coring drill was designed and built by Dr. Walt HANCOCK of the University of Nebraska at Lincoln. It responds to all control commands from the surface control panel and monitors all drilling and bore hole param. The instrument section contains sensors that monitor bore hole inclination in two axes, azimuth, bore hole temperature, bore hole pressure, weight on bit and other motor control functions. Depth is measured by a shaft encoder mounted on the crown block at the top of the tower. This information is displayed on a computer screen which is equipped with alarms and limits which can be set to accommodate different drilling conditions. The down hole portion of the instrument package is housed in a pressure proof housing to prevent infusion of the drilling fluid.

2.6. Motor section

The power for driving the core barrel and head assembly is produced in the motor section of the drill (Fig. 3). It is located immediately below the instrument section in the drill string. It consists of a brush-type DC motor which in turn drives a 17:1 ratio circulute gear reducer. The DC motor is an Industrial Drives Inc. TT2937-1010-CA which can develop (2.2 kW) at 2500 rpm. Input power for the motor is provided through the transformer and instrument section which supplies the 0-120 VDC required. The initial design for the motor section had the motor and gear reducer running immersed in the hole fluid, n-butyl acetate. Tests conducted during the 1990 field season indicated that the DC motor could withstand immersion in butyl acetate during the course of drilling 335 m depth. When the drill was used for drilling in the 1991 field season, extended running times and extra torque requirements brought to light serious commutation problems.

When the motor was run immersed in n-butyl acetate the life expectancy of the commutator was approximately 20 h. This was a considerable difference from the typical life of 5000 h when run in air.

While run immersed in butyl acetate the brushes tended to hydroplane on the commutator surface causing the brush to be held away from the commutator while running. This coupled with the high current draws seen during the coring process, caused excessive arcing between the brushes and the commutator. This resulted in serious spark erosion damage to the commutator.
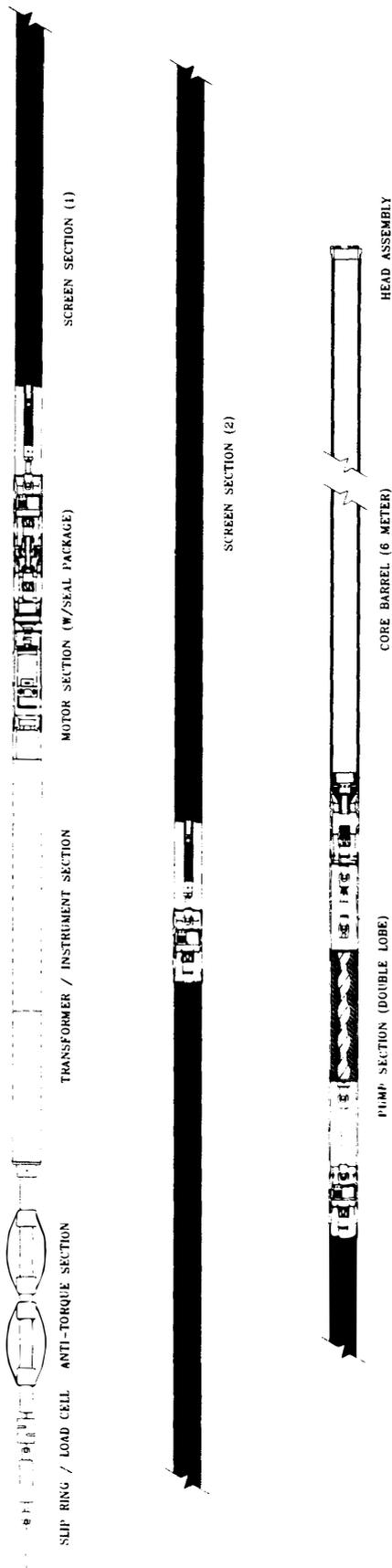
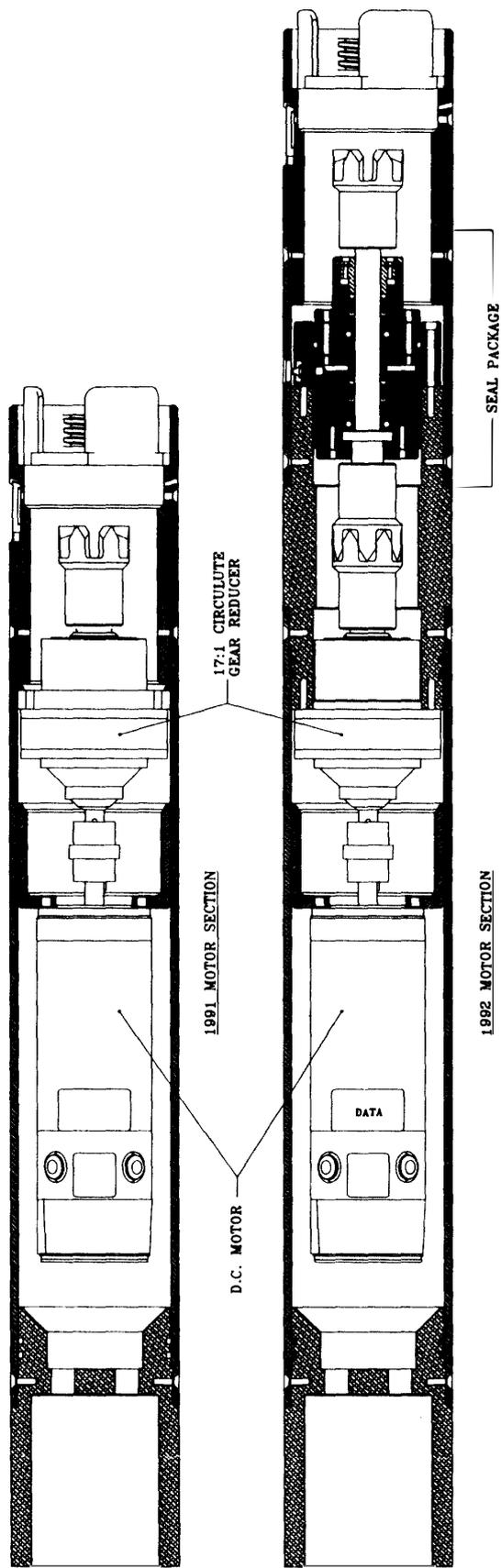Fig. 2. Drill string schematic of PICO 13.2 cm
deep coring ice drill.

Fig. 3. Schematic drawing of PICO deep coring motor
sections showing addition of seal package.

The solution to this problem took several parallel paths. One course of action was to investigate the options of various commutator and brush materials in conjunction with increased brush spring pressures. A number of inexpensive brush material types were procured and tested. A DC brushless type motor was designed and built to be able to withstand running immersed in the hole fluid. A third option was to design a pressure tight motor canister which would allow the motor and gear reducer to be isolated from the hole fluid.

The sealed motor canister section utilizes a cascade arrangement of chevron-type Teflon shaft seals. It uses the same type of DC brush type motor as before but will also accept the brushless style motor as well. This proved effective during the course of the 1992 field season where 742 m of core were recovered.

2.7. Screen section

Chips produced during the cutting process are pumped up the annulus between the inner and outer core barrels and into the screen section. The chips are contained inside the screen section and the drilling fluid is recirculated in the bore hole. The screen is made of stainless steel wire with a triangular cross section. The wire is spirally wound on vertical tensile members so that there is a gap of .2 mm between wraps. This contains the chips and allows fluid to recirculate in the bore hole. The screens are cleaned of chips after they are removed from the drill at the surface.

Initially, two methods of screen cleaning were tried, vibration and flushing. The flushing of the chips from the screen section proved ineffective. During the 1990 season it was determined that vibration was the easiest and most effective method for removing the chips from the 6 meter long screen sections. A slight modification to the drive shaft coupling running through the center of the screen section allowed a more open chip path for the chips to pass out the bottom of the screen. For cleaning, the screen is picked up by a separate winch with a standard drill coupling that has an electric vibrator mounted to it. The vibrator is turned on and the chips are discharged out the bottom of the screen and collected in a large drip pan mounted under the drill. The chips are then augered out of the dome to a centrifuge where the butyl acetate is recovered and recycled. The drill fluid recovery and recycling has recovered and reused more than 50 drums of butyl acetate representing a cost savings of over U.S. $50,000.

2.8. Pump section

The pump section for the GISP2 deep drill is a progressive cavity Moyno pump. This pump has the advantage of being able to pump a wide range of particle sizes and fluid viscosities. Two styles and material types have been used with excellent results.

The 1990 field season utilized a single lobe pump with an EPDM stator and tool steel rotor. The pump worked satisfactorily for the 335 m of core produced in 1990. The EPDM stator showed signs of wear and for 1991 was replaced with a two lobe Teflon stator. This pump has been in use for two drilling seasons without sign of excessive wear and has produced 1917 m of core with out any down time.

2.9. Core barrel assembly

A number of core barrel assembly configurations have been used in the GISP2 drill.

The upper portion of the core was drilled without hole fluid. Thus the transport mechanism for the chips is much different than fluid drilling and is reflected in the core barrel assembly design.

The dry drilling chip transport mechanism depends on a helical flighting on the outside of the inner core barrel working in conjunction with strips on the inside of the outer core barrel. These two features work together to provide a shear mechanism which transports the chips to the top of the core barrel assembly where they are transported through a cut out in the inner core barrel and deposited on top of the core. A plastic spacer isolates the chips from the core within the core barrel.

The material used for the initial inner core barrel was a carbon graphite composite. It was manufactured on a centerless ground mandrel which produces an exceptionally straight inner core barrel. It is very light weight and offers a smooth,low friction surface for chip transport.

Near the top of the inner core barrel are two windows that allow the chips to fall inside the inner core barrel on top of the core. Coring capacity is somewhat reduced because of the space necessary for the chips. The chips are removed with the core when the drill is brought to the surface.

The outer core barrel that is an integral part of the dry chip transport mechanism is stainless steel schedule 5 pipe with the addition of 3 strips welded on the inside of the outer core barrel running axially. This not only centers the inner core barrel but also supplies the shear necessary to move the chips up the annulus between the inner and outer core barrel. Some difficulties with wear properties were experienced with the carbon graphite composite inner core barrels.

Chip transport for fluid drilling is much different. The progressive cavity Moyno slurry pump provides the chip transport mechanism. It is driven by the motor section which is connected with a drive shaft which runs through each screen section. It can be run in either direction if necessary. The intake for the pump is the annulus between the inner and outer core barrel. Chips produced during coring are sucked up the chip path of the head and up the inner and outer core barrel annulus. The chip slurry mixture is pumped into a screen section mounted directly above the pump. The slurry mixture of ice chips and drilling fluid lends itself exceptionally well to this method of transport. The chips are essentially weightless if not slightly buoyant in the drilling fluid. As a result, two screen sections each 6 m long can be used together for sufficient chip storage capacity for a 6 m coring run.

Flighting on the outside of the inner core barrel is not desired. For wet drilling the inner core barrel can be a simple tube. Composite inner core barrels without helical flighting were constructed and used successfully in retrieving 6 m long ice cores. The outer core barrels do not need the inner shears strips and were omitted.

Composite inner core barrels had one drawback as they were constructed for the GISP2 drill. The attachment screws used for securing the coring head to the inner core barrel caused compression spalling around the screw holes in the composite core barrel. The force of making a core break was transferred to the core barrel and repeated core breaks were deteriorating the area around the screw holes. A possible solution would have been to manufacture a stainless attachment collar into the end of each composite core barrel to withstand the fastener loading stresses. The core barrels used for the 1992 field

season were made of steel. This not only solved the head attachment problem but also added weight low on the drill string to improve weight distribution. A brass clearance ring was mounted above the drill head to accurately locate the inner core barrel within the outer core barrel.

2.10. Coring heads

Two styles of coring heads have been used for the GISP2 drill. The old style head uses a knife cutter with a penetration shoe to limit and control the depth of cut. The new style head has this penetration angle built into the cutters. It also utilizes a pre-cutter ring as a pilot for the main cutters which remove the majority of the kerf. Both heads have produced excellent core in all types of ice.

The old style coring head is similar to that of the shallow dry coring drill head. It has three cutters located 120 degrees apart on the face of the coring head. Two profiles of cutter are used on this style head, the straight cutter and the chevron type. The chevron style cutter was developed to in an effort to enhance the head tracking characteristics. This was believed to help the drill produce a straight and vertical hole. In use, both cutter styles worked well with the chevron cutters requiring slightly more power to produce core. The straight cutters worked well in all ice conditions including the brittle ice zone.

2.11. Cutters

The old style coring heads use two cutter profiles. Straight and chevron. The original idea behind the chevron style cutters was a method to help the coring head track more accurately. No significant advantage was observed with this cutter profile as used at GISP. The chevron profile required slightly more power that the straight cutters. No difference in core quality could be observed between the two cutter types. Straight profile cutters were used for the majority of the core produced at GISP2.

Depth of cut using the old style cutters is defined by the penetration shoe. This penetration shoe attaches directly to the cutter to form a helical relief angle. After the cutter has removed the ice the penetration shoe bears the weight on bit of the drill. The penetration shoes are interchangeable and can be matched to various conditions of the ice fabric. Penetration rates of 0.4–1.4 degrees were used.

New style coring heads utilize a cutter type that incorporates the penetration shoe and cutter as one piece. The penetration angle is machined into the cutter and cannot be adjusted. To change penetration rates, the cutters must be changed. Carbide cutting edges were tested during the 1991 drilling season for this type of cutter but proved troublesome due to their brittleness and fragility of the cutting edge.

The two styles of coring heads used for GISP2 utilized the same technique for making the core break and retaining the core during the trip to the surface. Housed in the coring head are three spring loaded core dogs. These core dogs bear lightly against the core while the coring head is turning. When the coring run is completed the drill rotation is stopped. The core dogs engage the core and act as stress concentrators as the drill is slowly raised. This breaks the core loose from the ice sheet and retains the core in the inner core barrel for the trip to the surface. No significant problems arose with this type of core dog.

Acknowledgments

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