Replicate Coring System for 98mm Electromechanical Drill – Whipstock Conceptual Documentation

Ice Drilling Design and Operation (IDDO)

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Overview

Replicate coring systems (RCS) provide a means for additional core samples with high scientific value to be collected from an existing borehole. Considerable conservation of resources can be realized by the implementation and deployment of core replicating technology which is integrated into an established drilling/coring system. A long range (>3km) core replicating system has been designed and successfully deployed with the Deep Ice-Sheet Coring (DISC) Drill system to retrieve cores at five separate deviation points. The DISC Drill produced 122mm diameter core and the RCS produced 108mm diameter. This particular RCS provided operators complete autonomous control of position and inclination for initiating a deviated path including on the uphill side of the parent borehole. Adapting this technology to the Hans Tausen (HT) type drill design with 98mm diameter core, specifically the Ice Drilling Design and Operations' (IDDO) Intermediate Depth Drill (IDD) and Foro 3000 Drill, is not feasible without completely redesigning the drill systems due to the electronic and mechanical complexity of the technology.

Motivated by science community priorities articulated in the U.S. Ice Drilling Program Long Range Science Plan, the need for RCS capabilities to be adapted for use with the IDD and Foro 3000 systems was identified. The requirements and subsequent design for new a RCS can realize a relative simplification of the controls scheme in that deviations are allowed at any azimuth. Deviations made on the downhill side of a parent borehole are permitted and steering capabilities may be excluded. Further, the azimuthal orientation may be unknown during replicate coring operations. When the angular departure from the parent borehole is small, replicated core samples can be recovered from the same location in the ice sheet as original cores.

Independent replication and verification of experimental science relies on the highly specialized design and operation of ice drilling equipment to obtain samples of superior quality. Additionally, infrastructure costs associated with initiating a new intermediate depth or deep drilling site are significant. Replicate coring systems will facilitate maximizing the return of funding by the collection of additional ice from specific areas of high scientific value without having to drill a complete new borehole (Severinghaus, 2008).

Introduction

Replicate coring system concepts can be classified as either active or passive. An active system has features within the drill that make it possible to control and steer the drill from the surface without the use of a temporary or permanent physical blockage of the parent borehole. The first of its kind active core replicating system was successfully designed and deployed by the IDDO group at the WAIS Divide coring site as an addition to the DISC Drill (Shturmakov, Lebar and Bentley, 2014).

Alternatively, a passive system design eliminates the complexity associated with system design, component design and operation of an active system. For over 100 years the oil and gas industry has made use of a device called a whipstock to deviate or side track. Initially the device was used to get around challenging formations or abandoned equipment. As the understanding of the technology expands many operations deploy a whipstock with the intention of reaching additional pay zones from an existing drill site.

A whipstock in its simplest form is a solid wedge that is place in a borehole to initiate a change in drilling direction. Milling and reaming tools are typically deployed to initiate the deviation and to establish a path for the coring tools (which are of considerable length and rigidity) to pass without sticking. Deviations can be made at a parent borehole bottom or at the point of an obstruction or difficult formation. For replicate coring in ice, the point of deviation will vary across drill sites and requires a high degree of accuracy. In the latter case, an anchoring method must be incorporated into the RCS.

Prior Deviation Attempts and Accomplishments

Vostok Station

Ice coring and drilling equipment making use of a whipstock is first documented at the Russian Vostok Station in Antarctica (Vasiliev, 2007). Beginning in 1970, Vostok station operations have drilled five parent boreholes with either a thermal electric drill or electromechanical drill. Each of the five parent boreholes have been subject to at least one deviation. There are ten separate records of path deviation.

Borehole #1 at Vostok made use of a whipstock to establish their very first deviation in 1971. After a drill became stuck, and subsequently abandoned, a whipstock device measuring 4.5m in length was lowered to initiate a path around the obstacle some distance above. Next, a short thermal drill with a conical head was deployed. Specifications and details of the system and process are not abundant, however, direction change and exit from the parent borehole were successfully accomplished. Two additional direction changes were later completed by creating a false bottom with cylindrical ice blocks sent down by operators from the surface.

The remaining seven direction changes, or deviations, were performed with a thermal drill to bypass either a physical obstacle (abandoned equipment) or unfavorable borehole conditions.

At Vostok station, the means for deviating from a parent borehole were the inventions of necessity and were not carried out with the intention of replicating cores at a specified interval.

PICO Test Well

Experimentation of a similar arrangement was carried out in a PICO test well and achieved positive results (Zagorodnov, 1994). A thermal drill was used to melt a cavity large enough for unrestricted turning when the drill head was redirected by the whipstock (Figure 1).

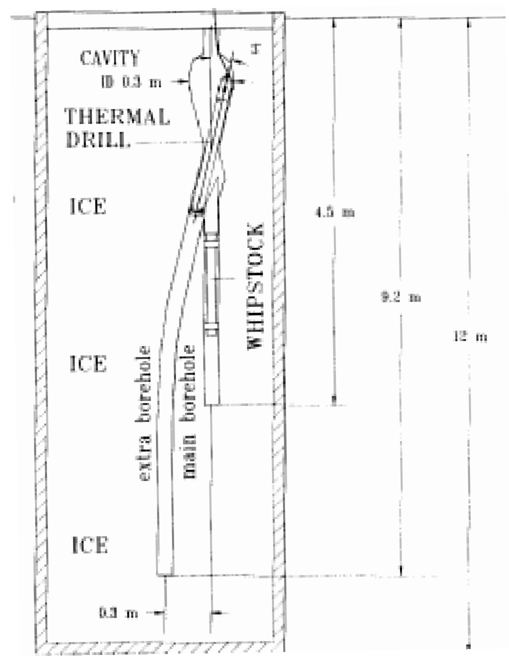

Figure 1: V.S. Zagorodnov, J.J. Kelley and B.R.

The whipstock and whipstock setting tool were additions to the standard antifreeze thermal electric drill system. The tip of the setting tool housed an electric resistance heater that inserted into a concentric hole in the whipstock. The setting tool and whipstock are coupled by a spring operated latching mechanism. When the appropriate depth is reached the electric heater was energized. After sufficient heat is applied a nylon retainer melts to release 24 springs on the whipstock to create a clamping force preventing downward and rotational movement. The springs are positioned such that an upward force is not resisted when retrieval to the surface is desired.

A similar process is used to extract the whipstock. The electric heater is available to melt away ice that may inhibit upward motion back to the surface.

The experimentation at PICO's test well demonstrated capabilities for directional drilling at any depth chosen by operators of an anti-freeze thermal electric drill system with the goal of obtaining replicate cores.

DISC Replicate

The active RCS designed and deployed with the DISC drill system obtained its replicate cores on the uphill side of the borehole. This allowed the parent borehole to remain open and accessible to data logging tools deployed after coring operations were completed. The replicate coring sonde is designed to tilt while suspended in the borehole by actuating lever arms in two sections along the sonde's length.

Initiation of the replicate borehole deviation was performed with the knowledge of azimuth and inclination. Custom broaching and milling heads were used to create a pocket on the uphill side of the parent borehole. Once a near full diameter core could be retrieved, a coring head and barrels (with smaller 108 mm diameter core) were used to gather the replicate core at that particular deviation. The process was repeated at four additional points along the parent borehole.

Goals and Requirements

A primary goal for development is to design the RCS to work with drill systems operating a 98mm electromechanical coring head like the existing Intermediate Depth Drill and future Foro 3000 systems. Existing drills of this type are lacking the full host of sensors, communication capabilities and modularity that would be required to implement an active system. With certain limitations, the passive approach of a whipstock for replicate coring is an obvious first choice.

The depth ranges of these drill systems are 1,700m and 3,000m, respectively, with a core diameter of 98mm. Replicate cores would ideally be of equal diameter, of maximum length and high quality, with a deviated borehole length of up to a few hundred meters. Setting the depth of replicate initiation at any point of a parent borehole is of high priority as well. This necessitates the design of an actuating anchoring device to be part of the whipstock.

Design should strive toward releasing and retrieving a whipstock for future use. This allows for additional borehole deviations at other points of a parent borehole. Design of sacrificial tools left in a borehole does not make the best use of developmental funding.

Azimuthal orientation has been assigned a low priority. This intermediate depth RCS is not required to deviate on the uphill side of a borehole. Current designs for 98mm diameter core electromechanical drills are not equipped with a navigational package that would be required to place a whipstock at a specific azimuth. However, setting and removal of a whipstock has been deemed possible using the existing drill design.

Minimizing the potential for damage and complete loss of equipment, outside of normal wear, will be key in adapting this technology for use in the field of glaciology research.

Total development cost and timeline to completion will take advantage of relative simplification over previous replicate coring systems. Several decades of designing and operating ice coring and drilling equipment allows a considerable sum of knowledge gained through experience to be leveraged throughout the process. It is not unreasonable to expect that a passive replicate coring system will provide results on par with an active system at a much lower cost.

Concept Initiation

IDDO drill systems of the 98mm diameter core family are cable suspended electromechanical drills based on the Danish Hans Tausen (HT) drill design. The suspension cable has four integral conductors. Two of the conductors are used for communications and the other two, along with the steel cable armor jacket, are used for power. The down hole electronics package provides motor speed and direction control for the drill motor, an accelerometer for sensing anti-torque slip, voltage input, output current, output voltage, inclination, three temperature measurements, two pressure measurements and fault detection/diagnostics.

The topside components of the drill system are established and set the basic operational parameters for a whipstock and deviating tools. The cable winching capacity is sized for 10kN for core break and 6kN for peak tripping out of the hole. The drill tower has a total height capacity of roughly 6.5m for the IDD system and 8.5m for the Foro 3000 system.

Several concepts for passive replicate coring systems are explored and the development feasibility for use with a 98mm diameter core electromechanical drill system are detailed in the following.

Off The Shelf
Off the shelf whipstocks designed to be used in open hole (uncased) oil and gas drilling operations were considered. These sidetracking tools and services are commonly used all over the world. One clear difference is the presence of a tubular drill string and heavy infrastructure of the drill rig. These whipstocks are either bottom set, plug set, or mechanically anchored. The sidetracking surface, as well as the whipstock, are of steel construction and considerable weight. To produce a gradual deviation, the angle of departure is kept small with the total whipstock length in the range of 4 to 5 meters.

Typical borehole diameters generated when coring for 98mm diameter samples fall short of borehole diameters found in this industry.

Running tools for setting, milling, and retrieving vary in design and aim to minimize trips down hole. For example, a milling tool can be used to carry the whipstock to the desired location and, after the anchor has been set, the two assemblies can be separated by shearing a bolt. The milling tool is then already at depth to start cutting the side track, eliminating the need to trip the drill string back to the surface for a tooling change.

Direction Change by Operation
Initial concepts included procedures for inducing an inclination of the parent borehole that could be utilized to induce a replicate core in later runs. However, producing a tilt of the downhole equipment that is reliable and repeatable almost certainly requires navigation, or steering, capabilities. Russian drillers at Vostok station successfully deviated from an inclined parent borehole using gravity as the only means to guide their suspended thermal drill system.

Drilling technique along with minor modifications to the coring sonde have anecdotal evidence of correcting a significantly inclined borehole back toward a vertical position with minimal inclination. Further consideration and design, however, are necessary to arrive at a feasible solution with a high likelihood of meeting the requirements of replicate coring.

Flexible Sonde
The proposal of a jointed sonde assembly to adequately flex while turning into the deviated borehole against the whipstock is also theorized. The major components of the sonde (core barrel, chips chamber, motor and anti-torque) would allow a small amount of freedom to create a small oblique angle with the next component via a flexible joint. A sonde that is capable of bending provides the benefit of reducing the likelihood of becoming stuck when the deviated path is taken. A higher angle of deflection from the parent borehole can be achieved with a whipstock that is shorter in overall length. Reducing (or possibly eliminating) the need for reaming a wider path can also be realized with a flexible and jointed sonde assembly.

This concept was proposed and discussed as a possible although unlikely option. A sonde with rigidly jointed sections is advantageous for a vast majority of coring operations. Prior experience drilling with a cable-suspended electromechanical drill presents concerns of difficulty in controlling the drill head from walking away from vertical. Challenges with imparting the necessary core break forces to the core dogs throughout a jointed and flexible sonde are necessarily complex.

Retrievable Mechanical Design
A completely custom mechanical design created by George A. Cooper in a detailed sketch and written description of a retrievable whipstock was also considered (Figure 2).

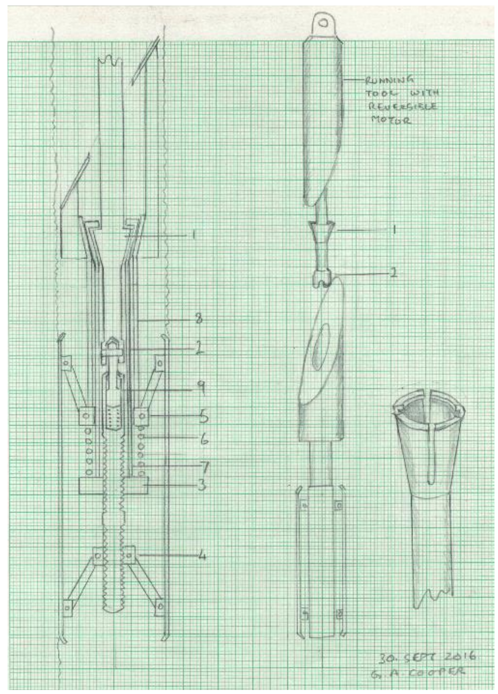

Figure 2: George A. Cooper mechanical whipstock concept sketch.

The concept relied on a stinger to deliver the whipstock downhole and rotate a threaded rod. The rod has both left and right hand threads each with a nut that travels in opposite directions. A reversible motor will impart rotation of the threaded rod and in turn actuation of each nut. Connected via linkage to each nut are borehole wall grippers that expand to fix the vertical location of the whipstock in the parent hole and contract when running in and out.

After placement of the device, the running tool would be removed from the sonde motor and a milling tool is deployed to initiate the replicate borehole.

Thermal Electric Drilling

Previous drilling operations that successfully achieved borehole deviation via a passive whipstock made use of a thermal electric drill system. Field experience and experimentation have proven this to be an effective method for creating a new and deviated path from the face of a whipstock. Before considering the power consumption and method for delivering thermal energy required for the operation of a thermal electric drill, the drilling fluid must first be addressed. Deep and intermediate depth drill systems typically operate with a hydrophobic drill fluid. Melt water from the thermal electric drilling process will not acquiesce with the drill fluid. Depending on drilling fluid density, the melt water will either rise or fall in the fluid column where it will find equilibrium in a frozen state (Zagorodnov, 2002).

Thermal electric drills are desirable for their simplicity, relative low design and operational cost and absence of rotating bit cutting forces. However, without a method to capture liquid melt water for removal from the borehole, a thermal electric drilling method did not receive further consideration.

Consideration of Risk

Sticking and permanent loss of coring equipment is a concern. Oilfield drilling operations can rely on a drill string and rig with a large capacity to push and pull. For systems using a cable-suspended electromechanical drill, operations are quite different. Direct application of off the shelf products is unlikely without significant modifications. However, techniques, processes and geometry may be adapted to ice coring, and consideration of these tools and services is worth noting.

Adequate anchoring of a whipstock closely follows the risk of equipment damage and loss. While in place, a whipstock's function is to first create the angle for the departing replicate hole, but must also stay in place for repeated runs of a coring tool as the required samples are collected. A firm connection to the parent borehole will be required while allowing for anchoring forces to be released for retrieval.

Minimizing or reducing the cutting action and deformation of the whipstock face should be addressed. The whipstock is a physical diverter of cutting tools and friction and cutting forces over the entire length has yet to be determined.

Capturing and controlling the volume of ice chips generated during the milling and replicate hole initiation is also addressed. A minimal volume should be the target for any design approach and is considered in this conceptual review.

New technologies applied to existing drill systems must consider the drilling fluid to account for compatibility of materials and operation. An ester based fluid with densifier is a likely choice at these depths for its density, viscosity and hydrophobic properties.

Geometry

Understanding the geometry of system components and projected paths through the ice are key in RCS design. Documented by V.S. Zagorodnov, J. J. Kelley and B. R. Koci in *Directional Drilling*, a white paper published in the 1994 Memoirs of National Institute of Polar Research, there is a minimum radius of trajectory at which point the center of a drill will contact the borehole wall as it turns a semicircle (Figure 3). At this minimum radius (and smaller), progress of the drill will not continue assuming complete rigidity.

$$R_{min} = \frac{L^2+4D_1^2-4D_2^2}{8(D_2-D_1)}$$

L = Sonde length, D_1 = drill diameter, D_2 = Borehole diameter

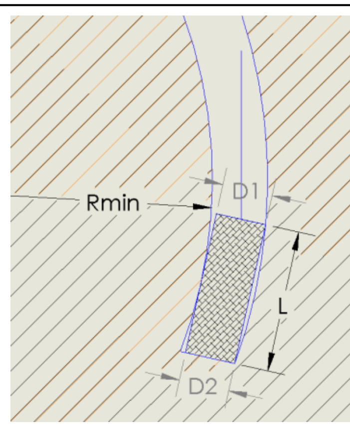

Figure 3: Minimum radius of trajectory

To produce a replicate core sample of diameter and length similar to the parent samples, the sonde length should be kept to a maximum. Using the current intermediate depth drill sonde with 2m core barrel as an example, the theoretical minimum radius of trajectory is slightly over 255m with arc length of approximately 4.5m per degree of departure from the parent. It should be noted that the IDD sonde does not have a constant diameter throughout its length (Figure 4). With the exception of the 129.6mm diameter cutting head, the core barrel is the next largest component with a diameter of 118mm. The very top motor section's diameter measures approximately 110mm (without consideration of anti-torque blades).

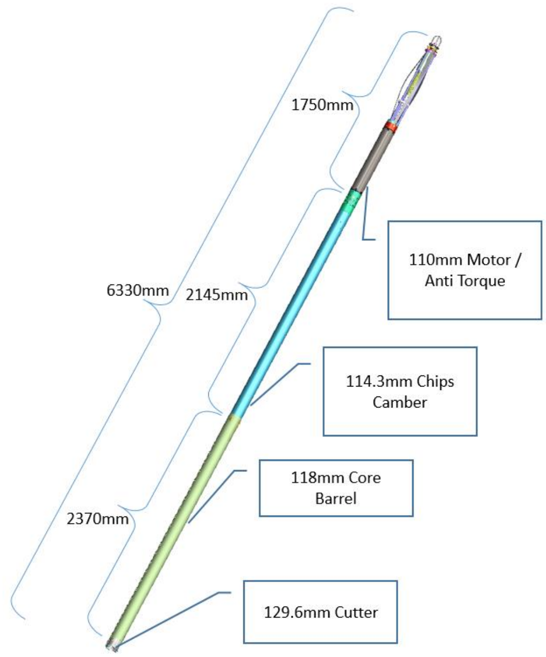

Figure 4: IDD sonde length and diameter

Using the maximum possible height of the current IDD tower, a whipstock that measures 6m long will provide the smallest face angle (assumed to be constant) at approximately 1.3 degrees.

Models that use this geometry to predict the path and interferences show that contact between the core barrel and parent borehole will occur after 0.3m of travel on the whipstock face (Figure 5). Reaming or enlarging the borehole become a necessary process to avoid sticking equipment.

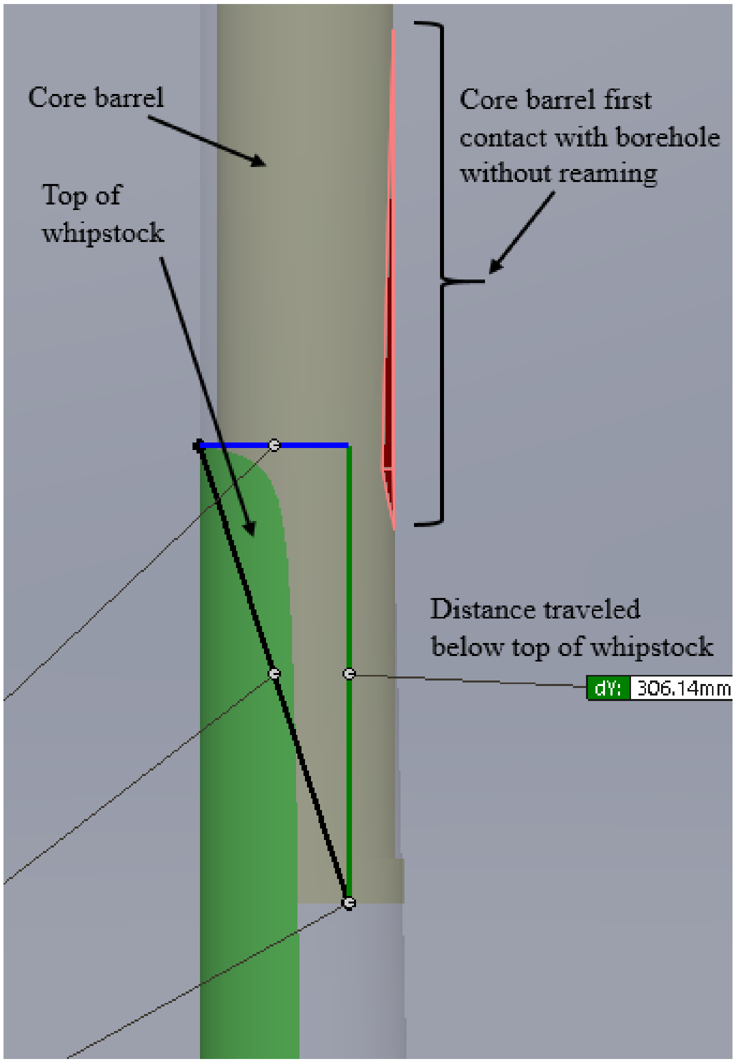

Figure 5: Sonde and borehole interference after travel on the whipstock

Two strategies for reaming were considered. First, an over-reaming tool similar to that used in the top cased section of the hole for enlarging could be deployed. It would require the capability to extend and retract a cutting bit to incrementally increase the borehole diameter at the point of particular interest. Keeping cutting forces and torque low are similar challenges that need to be addressed. Decreasing contact surface area and spring force from the anti-torque resulting from a larger borehole diameter also presents a challenge. Practical limits of reaming above the whipstock, however, do not guarantee unrestricted passage of the sonde through the replicate hole. Reaming an additional 40mm of diameter with a length equal to the IDD sonde will produce a volume of 1,300L of ice chips.

Figure 6: Depth and sidewall interference with over-reaming illustrates over-reaming and the interaction of the sonde with the side wall if no reaming procedures are completed below the whipstock. To prevent a situation where the sonde becomes stuck a reaming procedure is an absolute necessity.

Depth	0.5m	1.0m	1.5m	2.0m	2.5m	3.0m	3.5m
Interference Volume (mL)	12.6	235.6	668.4	1161	1561.2	1598	1302

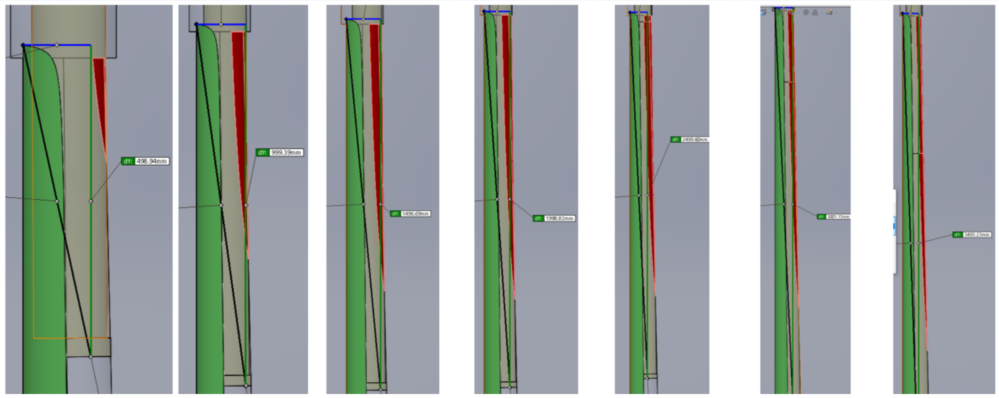

Figure 6: Depth and sidewall interference with over-reaming

The second choice for a reaming procedure is to equip a milling tool with trailing reamers to widen the arc path established by the sonde as it progresses down the inclined face of the whipstock. In the oilfield industry, these types of tools are commonly referred to as watermelon or dressing mills. Figure 7 represents an arc path that is necessary for unrestricted movement of a sonde equipped for coring (exaggerated for illustration purposes).

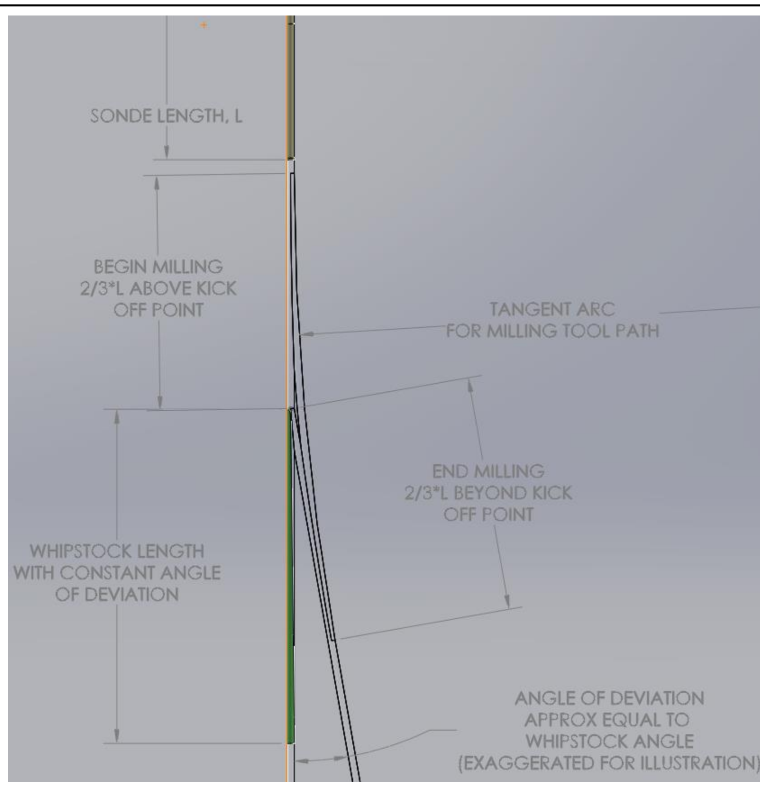

Figure 7: Required Arc Path for Reaming

The resulting cross section approximates an ellipse at the point where two paths merge. The top of the whipstock is chosen as the kickoff point. Beginning and ending of the milling process will occur at roughly 2/3 the sonde length L above and below the kickoff point, respectively. The volume of suspended ice chips with this approach is significantly less and is estimated to be 21L. This small volume of ice chips to collect and manage along with a more consistent borehole diameter for improved anti-torque blade engagement make for a clear choice.

Reaming

Initiating and establishing a replicate path will be a process of cutting with a leading bit and following with a milling tool to create the elliptical section where the two paths meet, or widened corner. An off the shelf design is unlikely, which provides the opportunity to design a reaming system specific for ice coring. After setting of the whipstock, a separate trip with a milling and reaming tool assembly will be required to start the replicate path.

This step in the process is focused on two key objectives: initiating the replicate path and clearing enough ice to allow tools to pass without restriction in future coring trips. The initiated path will begin at a location some distance above the ice of high scientific value. Initiating the replicate path will create a volume of ice chips that will be handled the same as other ice cuttings during normal coring operations. In other words, coring activities will be temporarily suspended to direct activities toward forming the path efficiently so coring can resume with a limited impact on schedule and minimized introduction of ice chips suspended in the drilling fluid.

Capturing ice chips and keeping them from becoming suspended in the fluid column is a high priority. The strategy above should be chosen for its relative low volume. Custom designed cutting tools should take on a geometry with a hollow interior and slots for ice shavings to enter the center. Adding a pump to direct fluid flow and ice cuttings into a chips chamber will also be considered to reduce the potential for loose ice cutting becoming suspended in fluid column.

Figure 8 depicts a concept for a watermelon reamer. An elliptical geometry of the reamer should achieve a variable and controllable force between the ice and contact points of the cutting tool and anti-torque.

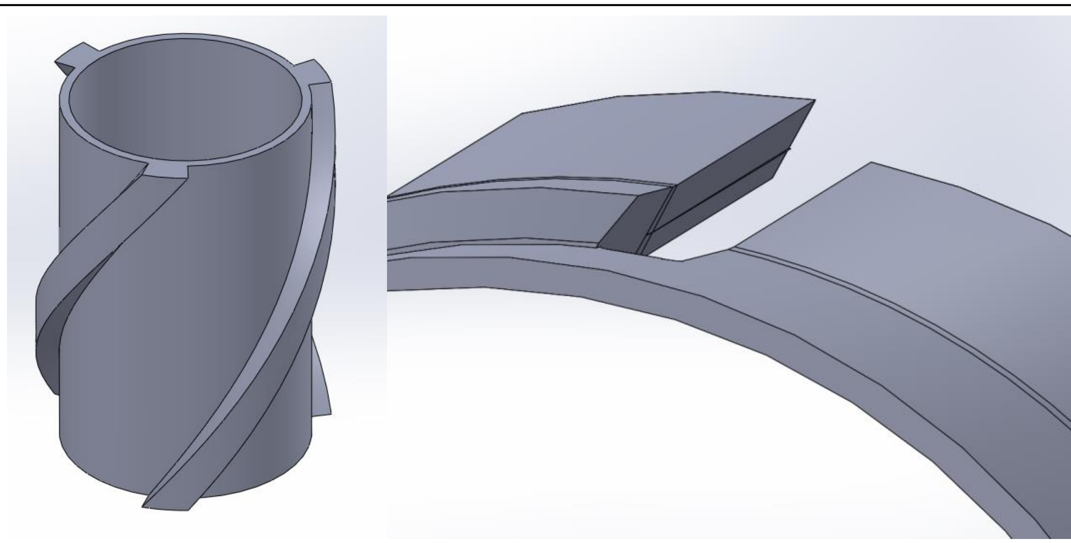

Figure 8: Watermelon reamer with helical cutters and slotted cutter for chip capture

To keep the anti-torque from slipping and the motor load under acceptable load, it is anticipated that the cutting volume per revolution is low. A hollow chips barrel, similar to the chips bailer, with a slotted cutting head shows promise. The lead cutting head with a conical shape will establish the initial deviation and first contact with the whipstock surface. Cutter head geometry, material and the forces exerted on the whipstock will need to be addressed.

Replicate path tool dimensions are constrained by the parent borehole diameter and drill tower height. The whipstock dimensions and weight are also constrained by the drill system's capacity.

Downhole Tools and Drill System Integration

Downhole tools for passive replicate coring systems are neither readily available nor are they fully designed. The first attempt for achieving a replicate core by a passive means should lead with proof of functionality and core quality to be followed closely behind with speed, efficiency and overall drilling productivity.

Running and Setting

The primary constraint for running and setting of the whipstock is the drill tower height. The drill tower height is a constraint for setting a whipstock with a maximum total length. The running tool will include a coupling link that is actuated from the surface along with a method for engaging and disengaging the whipstock's anchor/packer. Time spent running into and out of the borehole also needs consideration. Efficiency of total coring operations will be increased when downtime is decreased. Performing multiple operations in a single trip downhole will be used when physical limits (tower height and winching capacity) are not exceeded.

Anchoring

Anchoring and securing the whipstock in the parent borehole at a position some distance above the bottom would be achieved by using an anchor/packer. The weight of the whipstock and vertical force imparted by the reaming and coring sonde are to be accounted for in the load carried by the anchor. An actuated gripping collar in 360 degrees will provide the best distribution to the parent borehole wall.

For ease of tripping in and out of the borehole, the whipstock's overall diameter will be less than the bore diameter with a small annular space. Positioning the anchoring device directly opposite of the deviation direction (Figure 9) will impart a small angle and eliminate gaps and sharp ledges where coring heads could catch and stick.

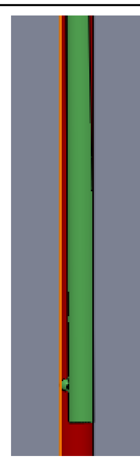

Figure 9: Whipstock anchoring foot in one direction

Milling

Once the whipstock is set to the specified depth and properly secured to the borehole, the sonde equipped with milling and reaming tools will be installed on the drill cable and sent to establish a path while working against the face of the whipstock. Watermelon shaped reamers will dress and widen the arc for facilitating a sonde with core and chips collection barrels.

Retrieving

Whipstock retrieval will closely follow the setting procedure. The coupling joint between the running tool and whipstock is first established so the anchor/packer mechanism can be released. Accumulation of ice chips and deformation from cutter head contact are likely and must be considered for returning the whipstock to the surface for repair and reuse.

Conclusion

Initiating the concept for a passive replicate coring system by the method of a whipstock has been discussed, theorized and demonstrated throughout the glaciology research community for several decades. The science requirements for WAIS Divide, which operated the DISC drill system, did not permit downhill side departures from the parent borehole. The first successful collection of replicate cores is largely considered both predictable and repeatable by an active means (drill sonde that is directed into position from the top).

Electromechanical drills of the HT design have been in service for many seasons due to the reliability and results that can be achieved for the science community. Developing a passive technology that can be added to an existing drill system's capabilities to perform replicate coring operations supports the objectives outlined in the Long Range Science Plan.

The next steps for planning the design and development of a whipstock for replicate coring should be executed with care. Input from all contributors engaged in the study of glaciology and equipment design, largely supported by the National Science Foundation, will facilitate forward progress and bring the community one step closer to meeting the our shared objectives.

Development of traditional science requirements outlining the needs of the science community for a RCS can be closely followed by an analysis of development budget and schedule. Reporting figures that estimate these crucial components to a new development project would be both premature and unreliable without the specific requirements.

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