Chapter 6: Recent Innovations in Drilling in Ice

from: Advances in Terrestrial Drilling: Ground, Ice, and Underwater, V.1, Yoseph Bar-Cohen, Kris Zacny, eds., CRC Press 2022.

Mary R. Albert[1], Kristina Slawny[2], Grant Boeckmann[2], Chris Gibson[2], Jay Johnson[2], Keith Makinson[3], Julius Rix[3]

[1] Dartmouth College, Thayer School of Engineering, 14 Engineering Drive, Hanover, N.H., USA, Phone: 603-646-0277, e-mail: mary.r.albert@dartmouth.edu
[2] University of Wisconsin, Space Science and Engineering Center, 1225 West Dayton Street, Madison, WI, USA, Phone: 608-263-6178, e-mail: kristina.slawny@wisc.edu
[3] British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB# OET, U.K.

7.1 Introduction

The need for scientific ice drilling in glaciers and ice sheets has been driven by many fields of science, including drilling ice cores for evidence of past environment and paleoclimate information, and drilling access holes through the ice to gather data relevant to glacial dynamics, history of glacier extent, sediment sampling, and discovery of ecosystems within and beneath the ice. Many nations have contributed to drilling technologies relevant to each of these fields, and developments in any one nation often build on prior designs from other nations. A description of the very early polar ice coring endeavors in Greenland and Antarctica is provided in Langway (2008). Ice drilling and coring technologies that were developed before 2008 are well described in Bentley et al (2009), including a wide array of ice coring drills, drills designed to create holes in ice only, and autonomous instruments that melt their way through ice. The text by [Talalay 2016] provides a review of mechanical ice drilling technology that includes design, parameters and performance of an assortment of tools and drills for making holes in snow, firn and ice. Described in detail are direct-push drilling, hand- and power-driven portable drills, percussion drills, conventional machine-driven rotary drill rigs, flexible drill-stem drill rigs, cable-suspended electromechanical auger drills, cable-suspended electromechanical drills with bottom-hole circulation, and drilling challenges and perspective for future development.

In this chapter our goal is to describe new ice drilling and coring technologies that have been designed, built, and used in the field in the most recent decade. Some of these technologies are improvements on prior drills, while other technologies such as a replicate ice coring drill, geologic drilling underneath many meters of glacial ice, and the rapid access isotope drill are the first of their kind. There are many additional ice drilling and sampling designs currently in the design or development stage that are not included in this chapter; rather our goal in this chapter is to describe proven ice drilling technologies that have been developed since 2009.

7.2 Ice Coring

The need to retrieve cores from ice is driven primarily by the natural archive of past climate and environment that is embedded in the physical, electrical, and chemical properties of the ice. In very cold polar and high-altitude regions where snow rarely melts, glaciers and ice sheets are the result of snowfall and ice crystals metamorphism over thousands of years to millennia. The snow deposition events result in layering that remains evident on seasonal time scales in high-accumulation areas to decadal time scales in low-accumulation areas. As snow continues to accumulate on the surface, underlying snow that is more than one year old, termed “firn”, continually compacts, sinters, and undergoes metamorphosis until finally at “pore close-off” depths, which vary from approximately 60-120 m, the interstitial pores have become closed to the atmosphere and the medium becomes solid ice with air trapped in bubbles within the ice. Deep in the ice the trapped air is forced into clathrates. The layering and the structural differences between firn, bubbly ice, and clathrate ice impacts the drilling and coring of ice. For retrieving ice cores for evidence of past environment and climate, it is almost always important that the drilling process retrieve full-diameter, intact cores.

Early and historical ice coring efforts have been documented previously, e.g. Bentley et al (2006), Langway (2008), Talalay (2016), and improved techniques continue to be developed. This chapter describes recent innovations in ice coring for drills that have demonstrated success in the field and thus have field performance data. One advance within this decade has been the development of a system for doing replicate ice coring at multiple targeted depths while still allowing the main borehole to be amenable to borehole logging systems.

7.2.1 Replicate Coring

The driving scientific interest in retrieving replicate ice cores is to obtain additional ice from depths where the ice contains evidence from significant environmental or climatic events. Often the scientific demand for such ice is higher than for the ice from the overall core; replicate coring can satisfy the demand without the need to drill an entire duplicate ice core. Results from Russian drilling at Vostok in the 2008-2009 field season showed that by repeatedly running the drill up and down around a depth in a slanted (6°) borehole, a shelf-like indentation could be made on the downhill side of the borehole that could serve as the start of a replicate core. It is often the goal in ice coring to have the core drilled as close as possible to vertical, so there are instances where the inclination of the borehole alone may not be sufficient to initiate a replicate core at a specified depth. In rock coring sometimes whipstocks are used to initiate deviatory cores, but the presence of the whipstock may impede or prevent the travel of borehole logging sensors that are used in boreholes after the core has been drilled. In addition, the geologic and petroleum industry has shown the utility of “steerable” geological drilling. To address the need to drill a replicate core on the high side of the borehole to facilitate subsequent borehole logging, and also to avoid the expense of developing fully steerable drilling system for ice coring, the use of actuators to force the sonde to the high side of the borehole was successfully pursued by the U.S. Ice Drilling program between 2010-2013. The drill to which replicate coring capability was developed was the existing Deep Ice Sheet Coring (DISC) Drill, an electromechanical system designed to take 122 mm diameter ice cores from the main borehole and 108 mm diameter replicate ice cores to depths of 4000 m. The DISC Drill had performed very well in drilling the main ice core to a depth of 3405 m in five field seasons at WAIS Divide, Antarctica, setting a new U.S. deep ice drilling record (see Bentley et al, 2006, p. 241-244 for description of the DISC drill). Replicate ice coring capability using a controlled sonde angle for the DISC Drill was designed, constructed and deployed for the U.S. Ice Drilling Program at the University of Wisconsin-Madison. The Replicate Coring System was developed and built in 2010-2011, tested in Antarctica during the 2011-2012 WAIS Divide field season and tested further in Madison, WI, during summer-fall 2012. During the 2012-2013 Antarctic field season, the system produced five azimuth and depth-controlled deviations at four target depth levels. A total of 285 m of replicate ice core was recovered in the first coring of its kind. The entire main/replicate ice core, including ductile, brittle and warm ice, had excellent quality and satisfied the needs of the ice science community [Shturmakov et al, 2014].

7.2.1.1 Science Requirements of Replicate Coring for the DISC Drill

The following science requirements were formulated by scientists associated with the WAIS Divide ice core project and were used by the engineers as the target of the design and construction of the replicate coring system for the DISC Drill.

Core Characteristics

- A minimum core length of 1 m is required, though 2 m is desirable
- A target core diameter of 100 mm. It is desirable that the diameter does not vary by more than 3 mm, i.e. 97-103mm core diameter is acceptable

- Total replicate core collection up to 400 m
- Ice pieces to fit together snugly without any gaps
- Ability to determine the in situ orientation (azimuth) of core segments to within ±10°
- It is desirable that the replicate core is within 0 m to 20 m of the parent borehole; however, somewhat larger deviations than 20 m are tolerable though not desired
- Core to be collected with an angle of deviation of less than 20° from vertical
- 10° or less is desirable
- An amount of rubble during the initial deviation from the parent borehole is permissible. Note: Deviation from the parent borehole will require some amount of drilling or reaming that does not produce science grade core. This is necessary in order to start the deviating borehole.

Hole Characteristics

- The parent borehole must remain open and usable after replicate coring has occurred. No reduction in diameter of the parent borehole is allowed (e.g. no permanent rings or whipstock may be used).
- Reaming of the parent borehole is permissible but should be kept to a minimum. Reaming should be less than 20 m in length, and result in a borehole diameter increase less than 100 mm. This is allowed for each deviation from the parent borehole.
- Replicate coring should be possible at any location of the borehole, starting 100m below casing end
- Damage to the parent borehole wall should be kept to a minimum, outside the reaming interval
- It is required that deviation is performed on the 'uphill' side of the borehole. This is to ease logging of the borehole.
- The borehole inclination must be measured with an accuracy of ±5°
- The Replicate Ice Coring System must be operational at a lowest temperature of -55°C
- If any permanent equipment is to remain in the parent borehole it must have an ID equal to, or larger than, that of the parent borehole and not obstruct borehole continuity

Drilling Fluid

- The drilling fluid must be the same, or compatible with, that used in the parent borehole

7.2.1.2 Mechanical Design of the Replicate Coring System for the DISC Drill

The Replicate Coring System added several new mechanical subsystems to the DISC Drill. These included two electromechanical actuators capable of pushing the sonde to any targeted azimuth, core and screen barrels that are reduced diameter from the main DISC Drill, and new cutter heads optimized for the multiple stages of the replicate coring procedure. These mechanical sub-systems employed as part of the complete Replicate Coring System were used to create five deviations from the 3,405 m deep parent hole collecting a total of 285 meters of replicate core from the most interesting time periods in the WAIS Divide climate record, with depth locations identified in **Figure 1**.

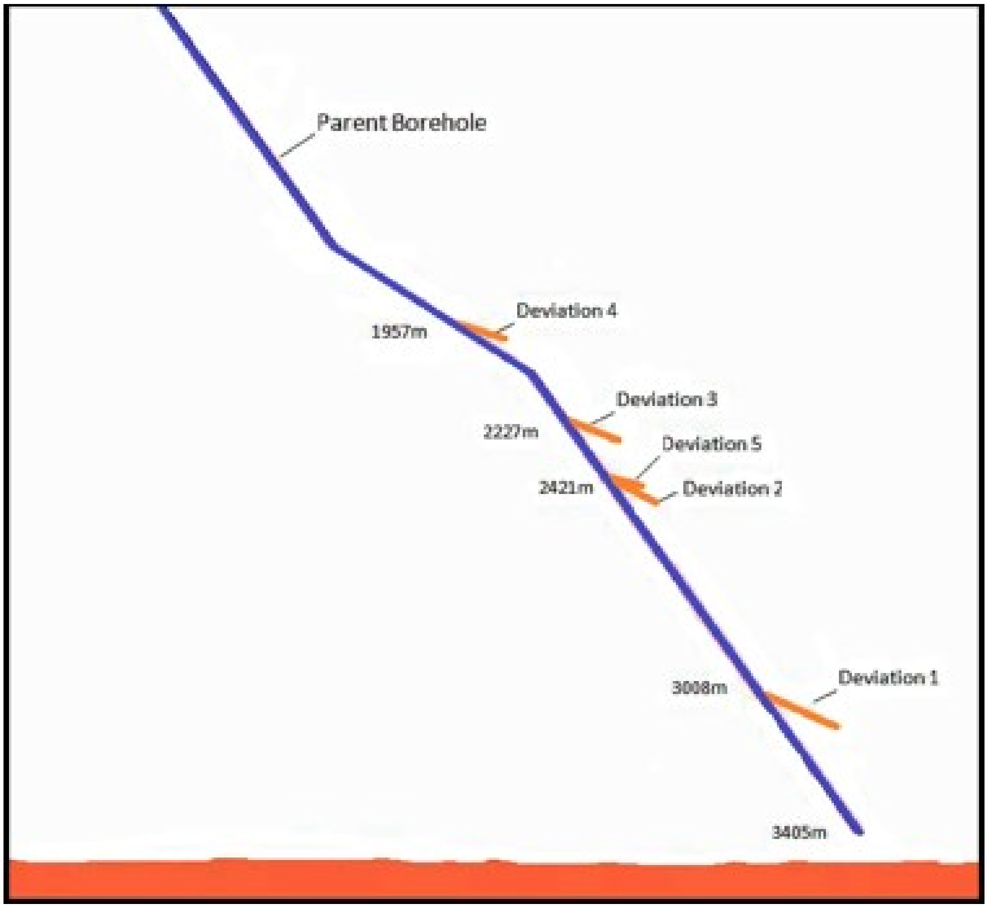

Figure 1: Replicate Coring WAIS Divide. Replicate core was collected from five intentional deviations from the parent borehole at four target depths. Note: The inclination of the parent borehole varied from vertical up to 5°. Deviations were created on the high-side of the borehole at an angle of about 1° from the parent borehole. Scaling of the figure exaggerates the apparent angles [Gibson et al, 2014].

A description of the major sections of the down-hole portion of the drill, the sonde (as illustrated in **Figure 2**), is essential to understand the basic operation of the system. The cable interface section is the upper most portion of the sonde and includes a freely rotating connection to the drill cable. Below this are the two actuator modules on either end of the instrument section. The actuator modules each include three levers to tip the drill in the borehole. On-board electronics are contained within the instrument section providing power and controls to the actuator modules as well as the pump and cutter motors just below the lower actuator. Chip barrels collect ice chips created from drilling. A core barrel is added as needed to collect and support the ice core. Multiple styles of cutting heads are employed for the various requirements of the replicate coring operations.

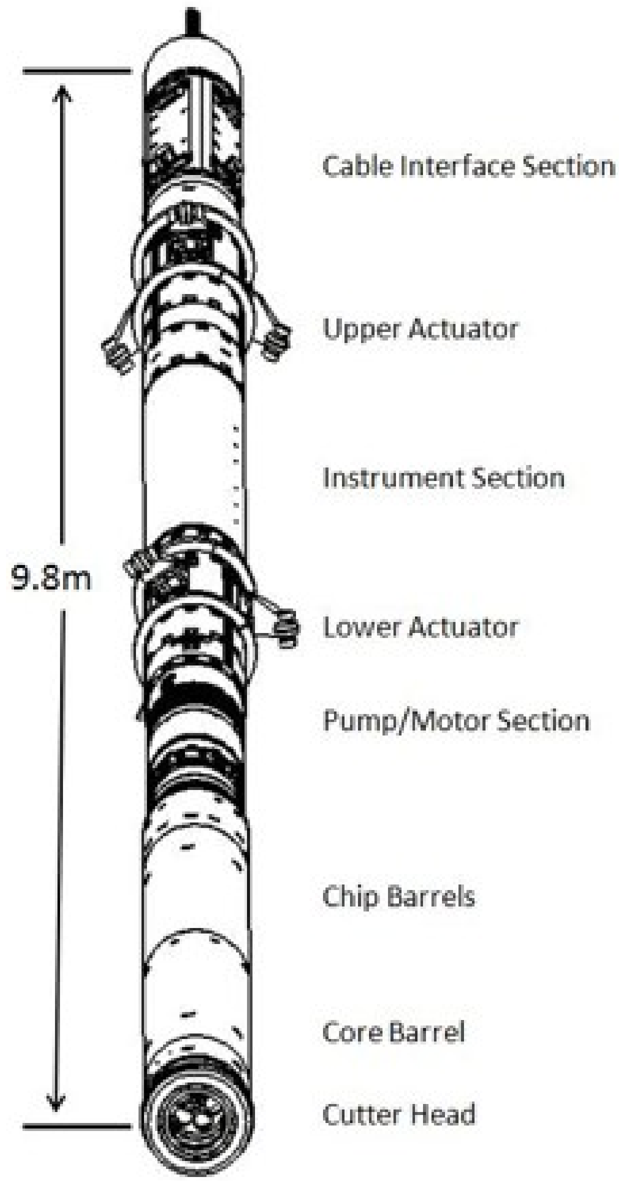

Figure 2: Replicate Coring System Sonde [Gibson et al, 2014].

The architecture of the Replicate Coring System maximizes the amount of flexibility in operation while adjustable design parameters focus and simplify operation. In production operation, the operator inputs azimuthal direction and the amount of force to be exerted on the bore wall. Sensors on-board provide real-time feedback of rotation, torque, weight-on-bit and inclination to the operator. On-board controls make near-instantaneous adjustments to maintain the commanded force and direction.

Through lab and field testing and a 10-week production season, a detailed procedure was developed to efficiently create a deviation in three basic steps as shown in **Figure 3** (Johnson et al 2014, Slawny et al 2014).

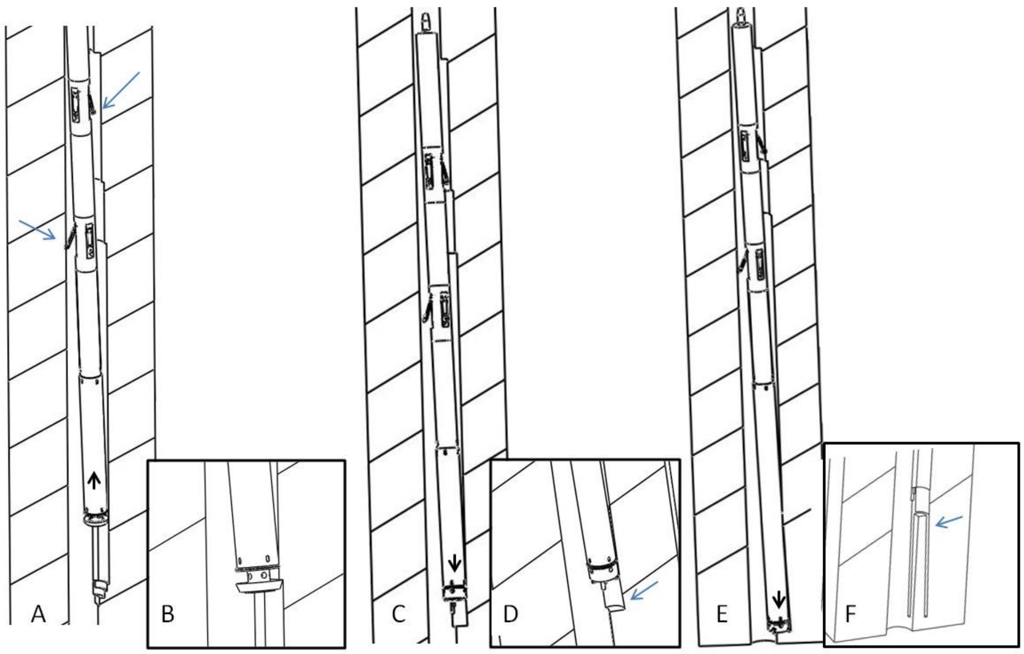

Figure 3: Replicate coring deviation procedure can be presented as three basic steps. First, the deviation is begun using the broaching head (A). Upper and lower actuators extend on opposing sides (blue arrows) to tip the sonde and engage the cutter. The broaching cutter engages the ice wall removing material in repeated passes in an upward-stroke (B). In a second step, the milling cutter is installed and a flat landing surface is created (C and D). In the third step, a coring cutter head and core barrel are added. The sonde is again tipped and coring starts on the flat surface provided by the milling cutter (E). The first partial core has a tapered geometry (F). This core is broken by core dogs and removed as the sonde begins to ascend [Gibson et al, 2014].

First, a deviation of about 15 m in length is created by cutting in an upward stroke using a broaching cutting-head, as seen in **Figure 3A** and **Figure 3B**. The cut is expanded in repeated passes until it is deep enough to allow the sonde to move 75 to 100 mm in a radial direction out of the parent borehole. An inclination sensor with <0.1 degree accuracy is used to make this measurement. Although using a milling cutter to create the deviation may be possible, using an axial cutter like a broach efficiently removes the material of the deviation with an inherently straight cut. This approach, however, leaves a gradual slope at the lower end of the deviation not suitable for landing the coring head.

The second step in cutting the deviation is to create a landing for the coring head, and this is accomplished by rotary cutting with a milling head over an additional 1 m of depth, as seen in **Figure 3C** and **Figure 3D**. Finally, the coring operation can commence. The sonde is tilted into the deviation to an angle of 1 degree relative to the parent borehole. An inclination sensor with <0.1 degree accuracy is used to make this measurement and assures the cutter lands at the full radial depth of the deviation, 75 to 100 mm. The first core is 1 m in length and the cross-section of the bottom of the core is nearly a full replicate core diameter, 108 mm; this assures that the core dogs can engage to break the core, as depicted in **Figure 3E** and **Figure 3F**.

Subsequent cores are recovered by re-entering the deviation. Accurate inclination and depth readings are essential to assure smooth re-entry. Radial force provided by the lower actuator is not necessary once engaged in the deviation to the depth of the base of the first core. At this point, the lower levers are retracted and the upper levers remain extended to provide anti-torque. Upper-levers transition from the parent to the replicate borehole by first coring to the point of transition with a 2 m barrel. On the following run, the 1 m barrel is used allowing the upper levers to descend fully into the replicate borehole before coring is resumed.

The replicate coring system is a combination of actuators, motors, sensors and a computerized control system that are critical to the system function. The control system requires information about the actual conditions of the system with means to correct the guidance system as drilling commences, and the actuator system requires capability of positioning and steering the system in the direction identified through the control system. Details of the system design are described in Mortensen et al 2014, and subsequent updates identified through system testing are described in Johnson et al 2014.

The unique Replicate Coring System supports ice coring science by allowing rapid collection of large volumes of ice core from depths of interest without risking access to future borehole logging in existing boreholes. The system is a key advance because it allows scientists to take core samples at targeted depths while leaving the parent borehole open for future logging of information. Deployment of this technology to WAIS Divide for a 10-week season allowed for the retrieval of critical core samples from five deviations at four target depths. This would have otherwise required four or more seasons to recover. The expectation is that the technology could be applied with equal success on future DISC Drill projects and/or adapted for use with other drill systems in the future.

7.2.1.3 Electrical, Electronic and Software Design for the Replicate Coring System for the DISC Drill

Science Requirements developed for the DISC Drill Replicate Coring System dictated that the deviations must be completed on the uphill side of the borehole, as shown in **Figure 4**. This ensures passive logging tools will remain able to traverse the entire length of the parent borehole following replicate coring. Such a requirement necessitates complex electronics to enable the drill to know where it is in the borehole, where it should be and an ability to steer itself to the correct location. Repeatable accuracy of locating a certain position in the borehole is paramount to successfully creating and re-entering a replicate borehole.

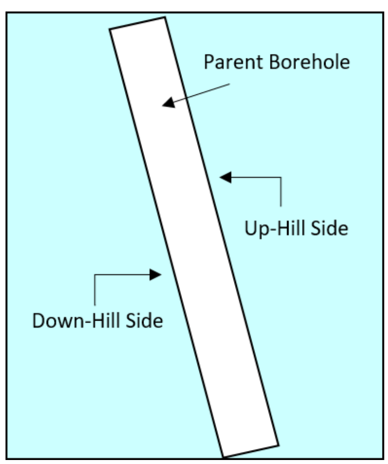

Figure 4: Depiction of uphill side of borehole [After Mortensen et al, 2014].

As noted in section 7.2.1.2, two actuator sections are added to the DISC Drill sonde. Each section contains three actuator arms as illustrated in Figure 5, each of which is controlled by a brushed DC motor. Real-time feedback is essential for control and positioning of the drill.

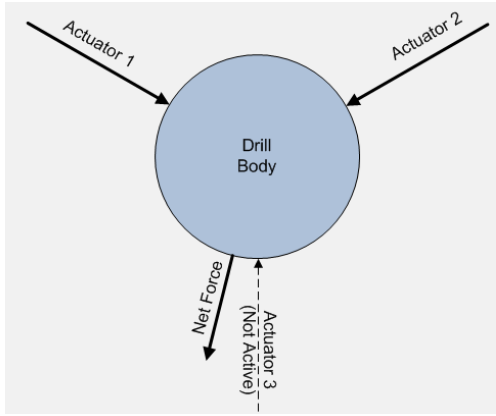

Figure 5: Two actuators work to produce one net force in a desired direction [Mortensen et al, 2014].

A complex control module is necessary to control navigation and pushing forces. The control system block diagram is shown in **Figure 6**. Six linear variable differential transformers (LVDT) continuously measure the location of each actuator arm. During descent into the borehole, all arms remain retracted.

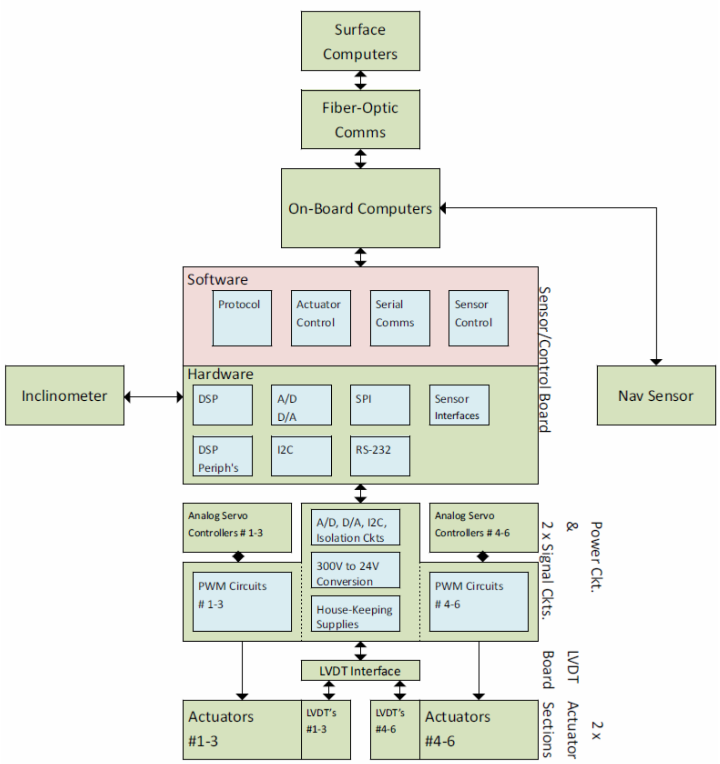

Figure 6: Replicate Coring control system block diagram [Mortensen et al, 2014].

Separate power supplies are implemented for the power board, LVDT board and the sensor/motor control board to incorporate multiple grounds and control noise in the system. Commercially-available Vicor power supplies were used. The Replicate Coring Control Module (RCM) consists of six circuit boards: one power board, two signal boards, one LVDT board, one sensor/control board and one inclinometer board. A commercially-available navigation module from 3DM is used to continuously read and report the drill's azimuth, that is, the drill's position relative to geographic north. Operators are able to enter a heading between 0° and 360°.

The RCM uses both integrated downhole software and modifications to the DISC Drill PC-based software. "The RCM software was designed as a 'round robin', meaning the software executes the same function cyclically at a fixed rate of 20 cycles s^{-1}. Each cycle has the following top-level functions:

- Read all sensors
- Parse commands
- Process actuators
- Wait until time to start over"

Advanced error-checking software is implemented using checksum and other redundant information. Operators are able to set drill heading and effort levels of the actuator arms or a 'SetEffort' value. To ensure commands sent downhole are accurately received and processed, operators can query the system for a 'GetEffort' value. Any discrepancy between the two values signals that the previous command was not properly received. Operators control all RCM functions via a laptop computer on the surface that runs National Instruments LabVIEW as the interface. A second laptop also runs LabVIEW software and controls the winch operation.

Even the most carefully drilled boreholes are not perfectly vertically-oriented. An important part of RCM system design is its ability to move to a pre-determined depth and at that point begin drilling a replicate core from the uphill side of the parent borehole. To initiate a new deviation, the drill is lowered to the target depth in the hole. Actuator arms are then activated to force the drill to one side of the borehole wall. The drill's inclination is then recorded. The actuator arms are then retracted and the drill is commanded to another set point 90° from the original point. The actuator arms are again activated and another inclination measurement is taken. Repetition of this process allows the operators to locate the uphill side of the hole. This process need only be completed one time when initiating a new deviation. Location and other set point information is then stored and automatically incorporated during subsequent runs. In creating a deviation, many runs are required to remove chips from the hole and to switch out drill heads depending on the technique being used. A broaching head is used to begin a new deviation. The winch is used to raise the drill to allow for upward cutting motion for approximately 15-20 m, known as stroke length. At the end of each stroke length, the drill is lowered again to the start point of the stroke, and the borehole is repeatedly widened, allowing the drill to increase its inclination and deviation out of the parent borehole. Following broaching, a downward cutting milling cutter is used to create a flat landing for the coring head. The design of the RCM, though complex, is in concept adaptable to other deep ice coring drills.

7.2.2 Intermediate Depth Ice Coring

Both climate history and glacial dynamics have driven the need for retrieving core from depths between 400 m and 1800 m. Existing quantitative reconstructions of the past two millennia are lacking in annual data prior to 1600 AD in many areas, and many cores are needed in order to understand the highly regional nature of many climate processes. In addition, the need to better understand ice dynamics processes for improved predictions of current ice sheet behavior in response to warming conditions requires a drill that can penetrate similar depths. Climate and environmental science issues relating to the past 500-1000 years require cores from depths of 400 m and deeper. The need to access areas with limited logistics requires that the drill be portable and versatile for use under a variety of conditions. Thus, a number of intermediate depth ice coring drills have been developed to be sufficiently portable that they can be used for coring at a wide variety of sites with production drilling in two field seasons or less, and they are able to retrieve core from depths of interest for a variety of science goals.

An overview of a number of intermediate depth drills in use by 2006 has been published [Bentley et al, 2006]. The British Antarctic Survey electromechanical drill was used to retrieve a 948 m ice core and some sediment from beneath the ice [Mulvaney et al, 2007]. Several drills developed at the Byrd Polar Research Center were successfully used in electromechanical dry drilling to 310 m depth in Tibet in 2015 (Zagorodnov, V., pers. comm 2019), and deeper using an ethanol thermoelectric drill to 586 m depth in Svalbard in 1987 [Zagorodnov, 1988; Zagorodnov et al, 2005]. Early electrothermal intermediate depth drills described in [Bentley et al, 2006] include the CRREL thermal drill, the Russian TELGA-14 drill, the CNRS drill, the Australian drill, and the Japanese JARA electrothermal drill. Motivated by the need to drill in temperate and polythermal glaciers in high altitude locations with minimal logistical support, [Zagorodnov and Thompson, 2014] identified design improvements for thermoelectric intermediate depth ice coring. These include injection of pure ethanol in the hole above the drill and circulation of an ethanol-water system through the kerf to produce good core quality with a high production drilling rate. With power requirements of only 1.5 kW, the system could be powered by solar panels.

In cold glaciers and ice sheets, essential concepts involved in ice coring apply to many electromechanical ice coring drills, from those designed to drill to tens of meters to drills designed to retrieve cores from several kilometers depth. The characteristics of the firn and ice change with depth in an ice sheet or glacier, and also the ability of the drill to operate without a drilling fluid decreases dramatically with depth, so that any single drill is not optimal for use in reaching all depths. However, keeping as many characteristics of the collective system of drills as uniform as possible facilitates ease of maintenance and interoperability. Toward that goal, the U.S. Ice Drilling Program is developing a series of drills in the "Foro" family of drills that have a common sonde diameter and similar design. The Foro 1650 is an existing, proven intermediate depth drill; originally targeted for drilling to 1500 m, it was later updated to 1750 m and successfully used to drill the "SPICE" ice core at South Pole. The Foro 400 is a shallow drill targeted at reaching 400 m, and the Foro 3000 Drill is designed for use in deep drilling to 3,000 m depth. A comparison of the system specifications is found in Table 1. These drills are described in more detail in the following sections.

Table 1. Comparison of IDP Foro Drill specifications.

	Foro 400	Foro 1650 (IDD)	Foro 3000 Drill
Max. Depth (m)	450	1650	3000
Core Length (m)	1	2	3
Trench (L x W x D, m)	None	15 x 4.6 x 1.5	19.3 x4.6 x 1.4
Slot (L x W x D, m)	None	3 x 0.9 x 3.5	5.5 x 0.9 x 5.3
Pilot Hole	Main Borehole Diameter	2-stage Reamer	Main Borehole Diameter
Casing	None	Polyethylene Sewer Liner	Polyethylene Sewer Liner
Tower	Fixed	Tilting	Tilting

Fluid Recovery from Chips	None	Centrifuge	Chip Melter
Ventilation	None	Forced Air / ERV	Forced Air / ERV
Tent (lbs)	755	4000	4000
Electrical Generator (kW)	5	30	35
System Weight (lbs)	3,920 (estimate)	62,500 (estimate to 700m)	35,700 – 52,700 (estimate; depends on shop option)

7.2.2.1 Foro 400 Ice Coring Drill

Targeted to retrieving ice cores up to 400 m depth, the Foro 400 Drill is designed to have the same sonde diameter and similar design to other drills in the Foro line. As the next generation of the PICO 4-Inch Drill system, the Foro 400 Drill has a winch capacity of 450 m of 5.7 mm diameter cable and recovers 98 mm diameter by 1 m long ice cores. The Foro 400 Drill retains the modular fiberglass tubular tower and sled-type base of the 4-Inch Drill, which have been desirable features of this system, but does so with a more refined design, as shown in **Figure 7**.

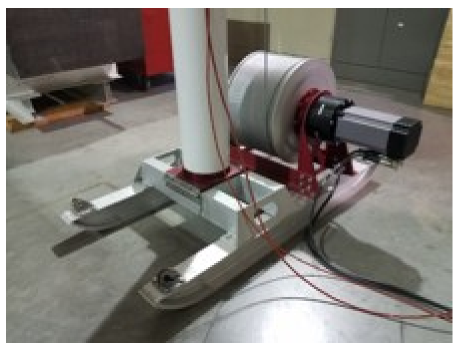

Figure 7: Foro 400 winch sled and tower base.

The anti-torque and motor section design is common with the larger Foro Drill systems, but does not contain an instrument section electronics package. However, the pressure tight motor section allows the drill to be used in wet conditions and with drilling fluids. The Foro 400 Drill sonde is shown in **Figure 8**.

Figure 8: Foro 400 drill sonde.

The speed and direction of the 500 W, 5000 rpm, brushed DC motor in the motor section is controlled with a pulse width modulated (PWM) motor controller housed in the control box at the surface. The winch is driven by a 3600 W brushless servo motor, which provides fully controllable line speeds from 1 mm/s to 0.8 m/s and a maximum pulling force of 8 kN. The crown sheave is instrumented with a load pin and ring encoder to monitor line speed and payout. A spring-loaded cable guide on the downhole side of the sheave prevents the cable from being able to jump off the sheave (see **Figure 9**) and will stop the winch if the drill is raised too high on the tower.

Figure 9: Foro 400 crown sheave with spring-loaded cable guide.

Cable load, payout and speed are displayed on an LCI-90i line control display manufactured by Measurement Technology Northwest, which is integrated into the control box, as shown in **Figure 10**.

Figure 10: Foro 400 control box.

The drill system packs into custom made shipping cases that have been designed with specific compartments for each piece to maximize protection while in shipment and to minimize overall size and weight. Overall weight has been reduced more than 40% compared to the 4-Inch Drill system it will replace.

7.2.2.2 Foro 1650 Drill

The U.S. Ice Drilling Program (IDP) generated the following science requirements for an intermediate depth drill through a series of iterative discussions between the scientific community and engineering staff of the program. The following are the original science requirements for the Foro 1650 Drill, also known in the U.S. community as the Intermediate Depth Drill (IDD):

Requirements:

- Target depths: from the surface down to 1,500 m
- Ice core diameter: 98 +/- 3 mm
- Core length: 2 m
- Minimum 10 m temperature at the site: -55°C

- Air transport type: Bell 212 or similar helicopter and/or Twin Otter aircraft
- Replicate coring capability: no
- Drilling fluid: drill should be compatible with existing fluids, e.g. Isopar-K or butyl acetate
- Maximum field project duration: 2 field seasons
- Core quality requirements:
    a. Complete core recovery over entire borehole, as close as possible, including brittle ice;
    b. Ice pieces to fit together snugly without any gaps;
    c. In non-brittle ice, the packed core should have no more than 12 pieces of ice per 10-meter section of core;
    d. In brittle ice there may be a lot of pieces in a single ~ 1m core segment, but the pieces must fit together retaining stratigraphic order; more than 80% of the ice volume must be in pieces that each have a volume > 2 liters
- Absolute borehole depth measurement accuracy: 0.2% of depth
- Sonde inclination will not exceed 5°
- Field set-up time: the minimum that is realistically possible with a three-person effort at a small remote camp
- System complete with receiving area for core from core barrel and ability to cut into 1 meter sections

Note that although the original science requirements were targeted at 1500 m, the system is currently capable of reaching 1650 m, The Foro 1650 is sufficiently portable for coring at a wide variety of sites, fits into a Twin Otter aircraft or Bell 212 helicopter, though numerous flights are required, and is capable of retrieving 98 mm diameter core from the surface down to 1650 m depth in two field seasons by a 10 person field-team for 24-hour per day drilling and core handling operations.

The proven design of the Danish Hans Tausen drill [Johnsen, 2007] was chosen as the basis for the Foro 1650 design. The Foro 1650 has been designed to recover 2 m long cores to balance the trade-offs between the length of the drill, which directly affects the size of all equipment on the surface and the length of the ice cores drilled per run. This keeps the size of all equipment manageable and within the design goals. **Table 2** presents a summary of the drill dimensions.

Table 2: Foro 1650 component dimensions.

Hole diameter, Dry	126.0 mm	Hollow shaft OD	30.0 mm
Hole Diameter, Wet	129.6 mm	Chips chamber ID	110.3 mm
Core Diameter	98.0 mm	Chips chamber OD	114.3 mm
Drill head ID	99.0 mm	Chips chamber length	2.60 m
Core barrel ID	100.0 mm	Motor section length	720.0 mm
Core barrel length	2.24 m	Anti-torque length	857.0 mm
Outer barrel ID	113.0 mm	Total drill length	6.50 m
Outer barrel OD	118.0 mm		

Outer barrel length	2.50 m	

The major components of the drill are the anti-torque, motor section, chips chamber with internal drive shaft, the core barrel, and cutter head. The anti-torque features a three spring steel skate design surrounding an EVERGRIP winch cable termination inside a bearing housing and a multi-channel slip ring to allow the drill to spin independent of the cable. The motor section has a pressure-tight housing 0.72 m in length that contains an electronics package, consisting of a motor power supply (MPS) and basic bidirectional communication loop, to control the motor direction and send a signal back to the surface if the anti-torque is slipping rotationally while drilling. The motor power supply (MPS) is designed to handle an input voltage of up to 600 VDC. The output voltage varies with the input voltage, giving proportional speed control up to the motor's rated voltage of 220 VDC. At this point, any additional power supplied to the MPS is applied to keep the motor at constant speed, and the output voltage remains at 220 VDC. Over-voltage and over-current protection features are also built in to the MPS to protect the motor. This power supply design makes it possible to supply over 500 W of shaft power at the drill over the small diameter conductors of the winch cable. A Parvalux PM60 brushed DC motor is coupled to an 80:1 ratio Harmonic drive gearhead. This gives a maximum output shaft speed of 63 rpm with 70 Nm of torque, assuming an 80% efficiency. The upper bulkhead and lower drive housing of the motor section are both removable from the central housing and kept leak tight with a pair of hydraulic piston seals on either end. **Figure 11** shows section views of the anti-torque and motor section.

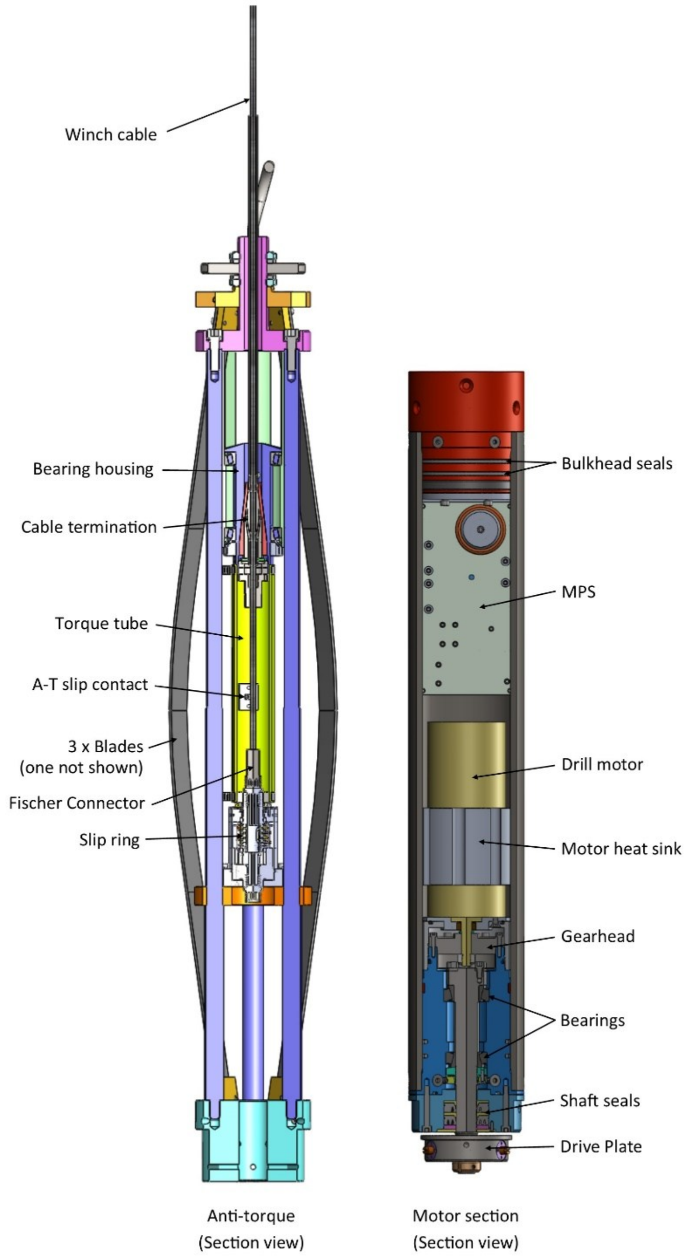

Figure 11: Foro 1650 anti-torque and motor sections.

Connected to the bottom of the motor section are the chips chamber and the hollow shaft which drives the core barrel. Two configurations of the 304 stainless steel chips chamber have been made, one for dry drilling and one for wet drilling. They differ only by the wet chamber having 7200 1.5 mm diameter holes drilled in it to aid in filtering the drilling fluid from the chips. The overall length of the chips chamber tube is 2.6 m with a usable length for chips of 2.3 m when configured with the pump, yielding a fill concentration of 56.5%. The output of the motor section attaches to the hollow shaft, which is 30 mm in diameter with three quarter-turn spring-loaded pins. Valve plates at the upper and lower ends of the hollow shaft open when the shaft is turned in reverse and close when the shaft is turned forward. The valves are set open when the drill is descending in the fluid filled borehole to permit faster tripping speeds by reducing hydrostatic drag. The valves automatically close when the shaft is run forward, allowing the space between them to fill with cuttings and transport the cuttings back to the surface without being flushed out. Single turn helical augers, often call boosters, can be placed on the hollow shaft at any position between the valves to facilitate the transport and packing of cuttings in the chips chamber. A twelve valve double piston pump can also be installed just above the lower valve for wet drilling [Johnsen et al, 2007]. Alternatively, the pump can be replaced with a chips valve assembly designed by IDP, which prevents cuttings in the chips chamber from being able to be flushed out of the chips chamber when the drill is being tripped back to the surface. At the end of the hollow shaft is a bayonet housing that attaches to and drives the core barrel. The hollow shaft assembly is shown in **Figure 12**.

Figure 12: IDD hollow shaft assembly.

Following the chips chamber is the outer tube which contains the core barrel. IDP innovated the first use of filament-wound fiberglass tubing for the outer tube, shown in **Figure 13**. The tubing has 24 saw-tooth like grooves running the length of the inside of the tube, which facilitate the transportation of cuttings up the helical flights on the core barrel. The tubes are very round and straight and cost a fraction of tubes made from metal. The outer tube attaches to the chips chamber with a slip fit connection that is held in place with three locking pieces that fit into a keyhole shape detail. The core barrel, which is sized to recover a 2 m long core, is manufactured from 304 series stainless steel tubing. The top of the barrel has three channels machined into it that the bayonet housing pins run in. These details serve as a quick detach mechanism allowing the drill to be recovered, leaving the core barrel and cutter head behind, should the cutter head become irretrievably stuck while drilling. Also, using the mass of the upper portion of the drill, it can be used as a slide hammer to break core. Two configurations of this barrel have been made. The first has three flights with a 35° pitch angle, which are fabricated from ultra-high molecular weight polyethylene (UHMW). The second configuration, used for wet drilling with the pump, has three aluminum flights with a 48.5° pitch angle and at 2 mm high only partially fills the annulus between the core barrel tube and outer tube. These partial height flights provide a stirring action, and rely on the pump flow to provide the chip transport. Near either end of the core barrel, a short section of full height UHMW flights were added in for guidance to keep the core barrel centered in the outer tube.

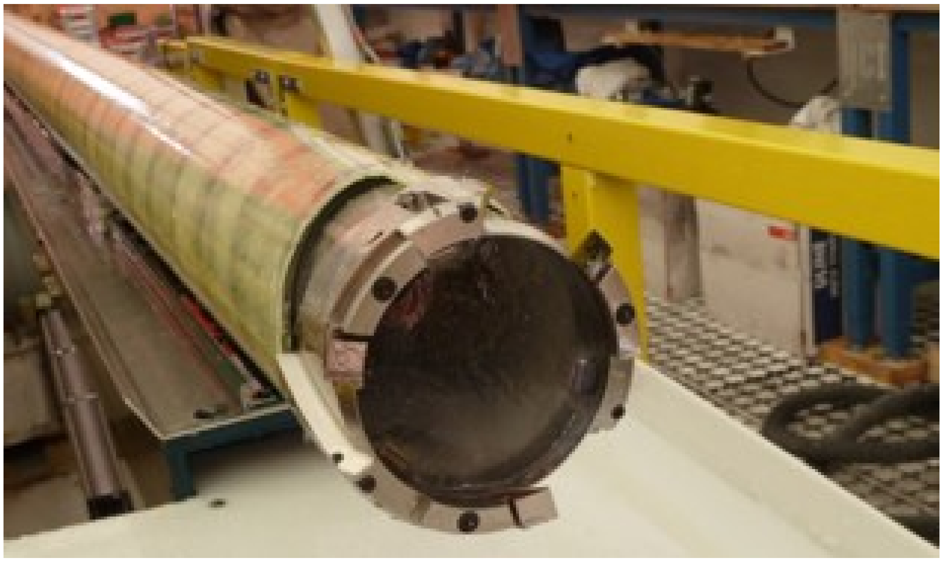

Figure 13: Filament-wound fiberglass outer tube and stainless steel cutter head.

The cutter heads follow the Hans Tausen drill design, having three cutters with a 42.5° rake angle and 15° relief angle, as shown in **Figure 13**. Two widths of cutters were made, both of which create 98 mm diameter cores. The narrower kerf cutter produces a 126 mm diameter borehole while the wide kerf cutters make a 129.6 mm diameter borehole and are used for wet drilling to provide more clearance around the drill for improved fluid flow. The three core dogs are double sprung, meaning a light spring is used to keep them retracted while a heavier spring is used to set a pre-load against the ice core. This method reduces damage to the ice core if the previous break was uneven. Two different cutter head configurations have been built. One is used for wet drilling and one for dry drilling. The only difference being the wet head has a smaller OD permitting improved fluid flow around it. Shoes mounted on the back of the cutting surface will provide cutting pitches between 0.5 mm and 3.0 mm per tooth. The head attaches to the core barrel using three eccentric headed bushings to pin it in place.

A tilting tower design was chosen for its ease to set up and ability to position the drill horizontally for servicing. The 6 m long tower is fabricated from 1 and 2 m long sections of 132 mm square aluminum tubing that break down for ease of transport and assembly. The aluminum top sheave is instrumented with a load pin and ring type encoder for measuring cable payout. The ring encoder permits a very compact sheave design while providing 0.2 mm payout resolution. Up to 1,700 meters of 5.7 mm diameter electromechanical cable can be spooled onto a removable all aluminum winch drum with integral Lebus groove. The cable has three #24 AWG conductors and a breaking strength of 24.5 kN. The winch is driven by a 7.5kW 460 VAC brushless servo motor with resolver feedback and built in brake. It is coupled to the winch drum by a helical bevel gear reducer with a 56.38:1 reduction. This provides fully controlled line speed from 0.5 mm/s to 1.4 m/s and enough pulling power to do a 10 kN core break. A custom built level wind, using the similar control method IDP first designed for the DISC Drill, has been implemented. The level wind is a self-contained device (see **Figure 14**), requiring only 24 VDC, 170 W power, and operates fully independent of the winch.

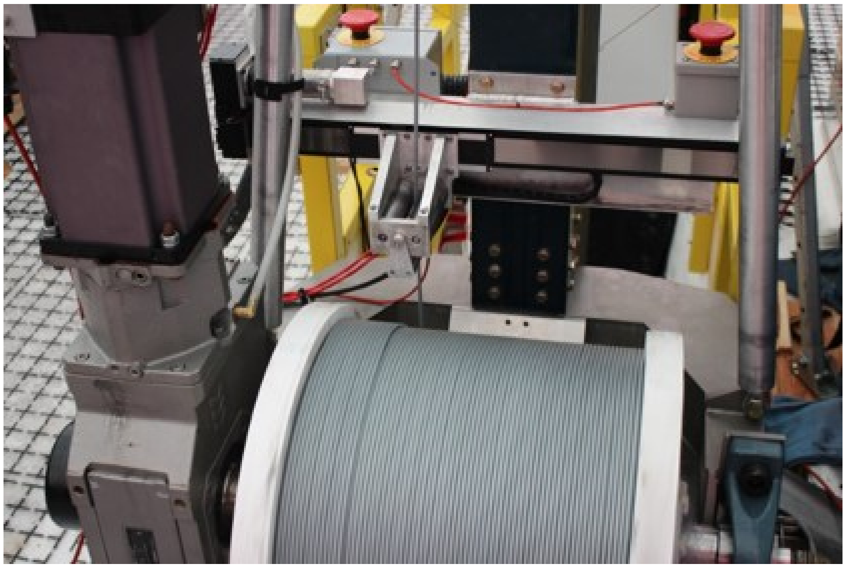

Figure 14: Foro 1650 winch and level wind.

The control system monitors the cable angle between the winch drum and fairlead roller and sets the required speed to keep this angle near zero. Further information on this novel method for cable level winding can found in a related article [Mortensen et al, 2014]. The winch drum and drive are mounted on a trunnion that pivots with the tower. There are two main advantages with this design. First, the drill does not move up or down the tower as it is tilted. Second, the winch drum translates vertically 15 cm as the trunnion tilts which makes it possible to install and remove the winch drum without additional rigging or lifting equipment. To remove the drum, two wood rails are first placed on the tower base. The trunnion is then tilted back until the drum rests on the rails. The drive flange is unbolted from one side and the bearing block from the other, freeing the drum so it can be rolled out and into its shipping case. The tower is tilted using an electric linear actuator with a built-in fail-safe brake and provides full variable speed control. The winch and tower assembly mount to an all-aluminum base frame, 1.7 m long by 1.2 m wide. A model of the complete winch and tower assembly is shown in **Figure 15**.

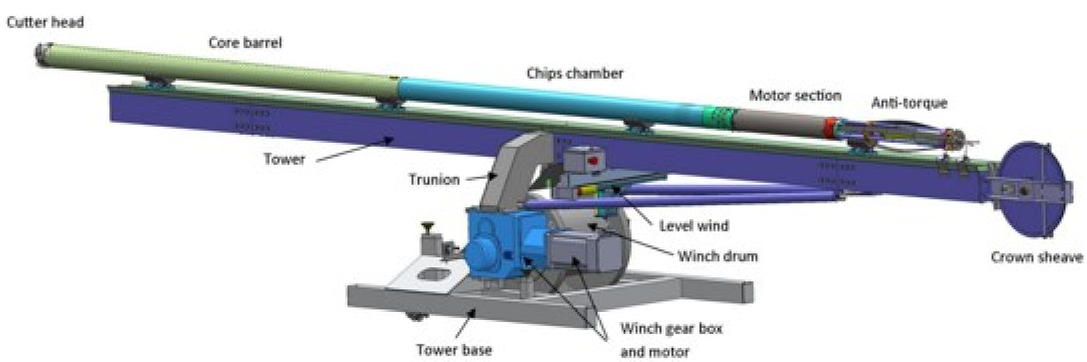

Figure 15: Foro 1650 tower and sonde.

After the drill has been parked on the tower and tilted horizontal, the hollow shaft and core barrel are detached from the rest of the drill and pulled out either by hand or with a hand crank winch located at the end of the pull-out table. The cuttings are collected in a tub located between the end of the drill slot and the pull-out table for later processing. The core barrel, containing the core, is transferred by hand laterally to the core processing line. The ice core is pushed from the core barrel through a specially designed Fluid Evacuation Device (FED), which, using suction, removes most of the drilling fluid from the core surface. Ductile ice cores proceed down the line where they are measured and cut into 1 m lengths using a circular saw. At this point, they can be put into lay-flat tubing and packed for shipment. Cores that are recovered from the brittle ice zone are placed into polyethylene netting as they exit the FED, as seen in **Figure 16**. An initial length measurement is taken and the cores are then transported directly into a core storage trench that is excavated at the end of the drill trench. The cores will rest for one year before being cut and packed. A ladder lift is used to move packed ice core boxes from the trench to the surface where they are palletized for shipping.

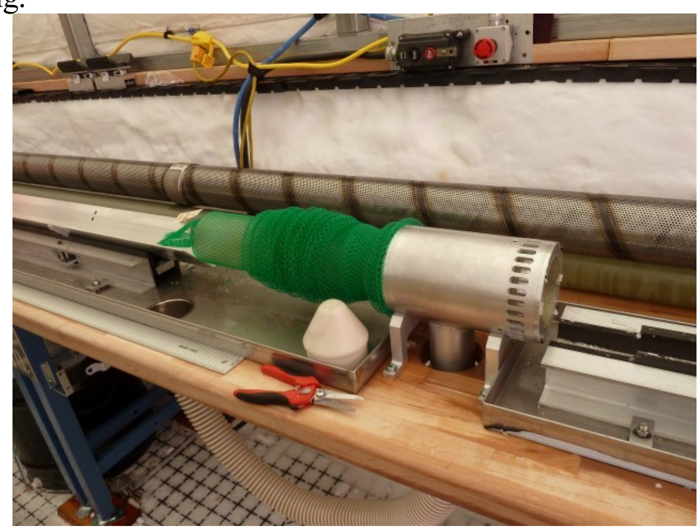

Figure 16: Fluid Evacuation Device (FED). Polyethylene core netting is used for storage of brittle ice.

The slurry of ice chips and drilling fluid removed from the chips chamber is transferred to a centrifuge where the slurry is spun to recover most of the drilling fluid. The cuttings are then carried out of the drill tent and discarded in a designated chips disposal area. Recovered fluid drains to a collection tank and passes through a final filter before flowing through a hose and back to the borehole. Drilling fluid is brought to the site in metal drums and staged next to the drill tent. A drum pump is used to transfer the fluid to a manifold in the drill trench. Fuel bladder material lines the slot end wall and floor to direct drilling fluid coming off the tower back to a catch pan around the casing and into the borehole. Fluid carried up on the winch cable is recovered using a vacuum connected to a custom built cable cleaner based on the one use by the Danish drilling program at the NEEM drill site in Greenland. A bailer was built for recovering cuttings that are not fully recovered by the drill. It consists of a perforated mesh tube, configurable to either 1 m or 2 m long, with a check valve assembly at the lower end. The bailer, shown in **Figure 17**, mounts to the motor section in place of the chips chamber. Chips are collected in a fabric mesh sleeve inside the tube as the tool is lowered in the fluid. The valve assembly retains the chips in the bailer while returning to the surface, yet permits easy removal of the chips when on the surface.

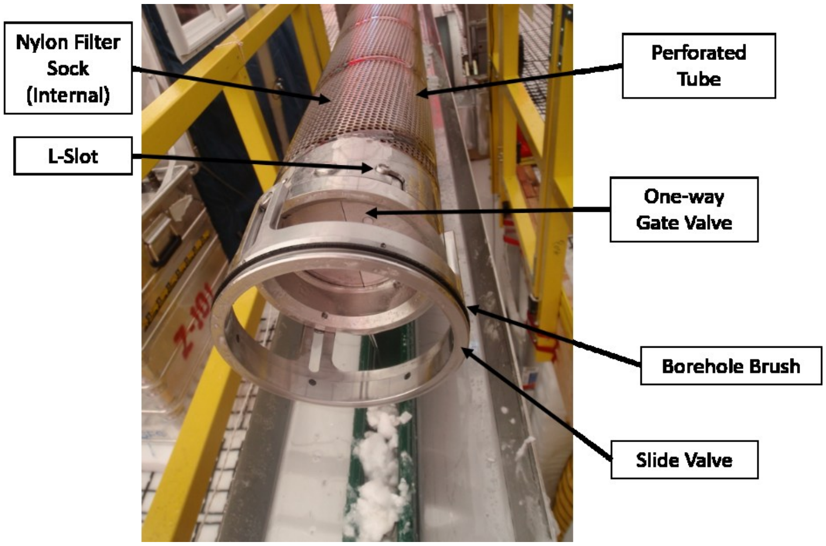

Figure 17: The bailer is a device used to collect chips in the borehole. It directs all fluid and chips through a perforated tube lined with a nylon filter sock while tripping down the borehole. When returning to the surface, the gate valve closes and the slide valve opens, allowing fluid to pass around the outside of the tube. At the surface, the slide valve assembly and nylon sock are removed using an L-slot and chips are emptied.

The drilling equipment is housed within a fabric covered tent. The floor level inside the tent is recessed 1.4 m below grade to reduce the required height of the tent and to help keep the interior of the tent cool. The floor is covered with 0.5 m x 1.0 m x 30 mm thick sections of polyethylene grid material to provide a reusable slip-free work surface. Stairs at either end of the trench provide access. The custom made 19.5 m long x 4.9 m wide x 3.1 m high tent, which was fabricated by WeatherPort, features a steel frame with a fabric cover. Both end walls have personnel doors and a large double zipper entry for moving larger equipment in and out. The fabric is a PVC impregnated polyester cotton blend with an acrylic top coat. The fabric has a cold crack resistance to lower than -80°C and it remains very pliable at -40°C for ease of setup. The structure has been engineered for a snow load rating of 269 kg/m2 and 65 knot winds. The cover is white and non-insulated to provide good natural lighting. There is a red strip on either end to improve visibility in poor weather; this and other tent features can be seen in **Figure 18.** Four 305 mm diameter wind directional vents were installed on the ridge line to provide convection cooling. Inside the drill tent is a smaller, 1.2 m wide x 2.4 m long, insulated tent which serves as the drill control room. Three windows were installed to provide the operators good viewing of all operations. The space is heated with an electric heater, and the break resistor for the winch motor provides supplemental heat.

Figure 18: Interior view of the Foro 1650 tent.

Ventilation in the IDD drill tent is provided by two fan systems. An 1100 CFM centrifugal ventilator draws air from the bottom of the slot and exhausts outside the drill tent. The core dryer and cable cleaner vacuum systems are also vented into this system. The second ventilator is located next to the centrifuge and displaces 450 CFM. The combined air flow of the ventilators will provide seven air volume exchanges per hour.

7.2.2.2.1 SPICEcore Project

The first deployment of the Foro 1650 drill (a.k.a IDD) system was to the South Pole, Antarctica to recover ice cores for the South Pole Ice Core (SPICEcore) project. The Foro 1650 drill system, with a shipping weight of 13,600 kg and volume of 63 cubic meters, was shipped to the South Pole and set up at the beginning of the 2014-2015 season. The entire project spanned three seasons, beginning in the 2014-2015 season and finishing mid-way through the 2016-2017 field season. A photograph of the SPICEcore drill site is shown in **Figure 19.** The first core was drilled on December 8, 2014. Dry drilling was completed to 160 m, and the borehole was reamed to 229 mm diameter to a depth of 130 m for installation of the casing. At this point, wet drilling began, and a final depth of 736 m was reached by the end of the season. The average length for the 98 mm diameter cores was 1.82 m. The borehole diameter for both dry and wet drilling was 126 mm. All drilling, both dry and wet, was done using the "dry drilling" core barrel, which has full height UHMW flights. The dry hole chips chamber was used for dry drilling and the chips chamber with the 7200 vent holes was used for the wet drilling. Most of the drilling was done working in two 10-hour shifts. The first 600 m of ice was packed and shipped back to the U.S following the 2014-2015 season. The remaining ice was stored in the core storage trench for the winter.

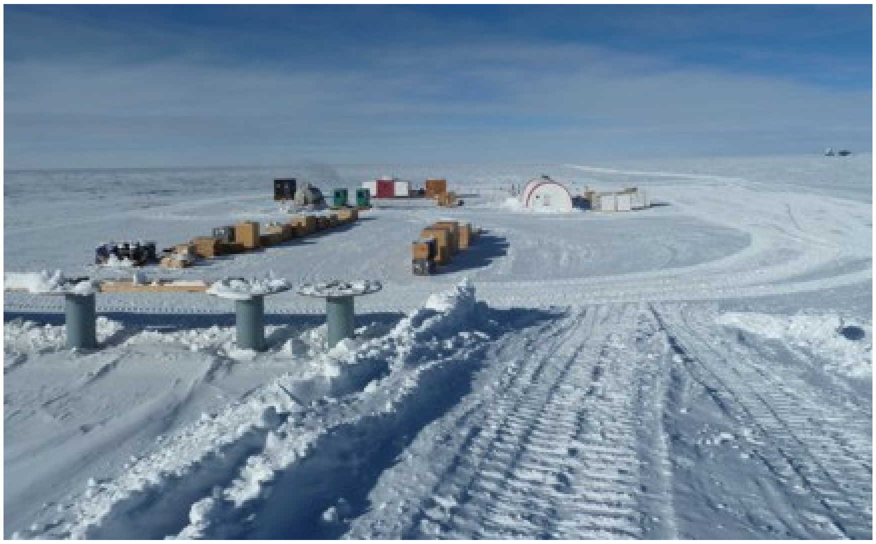

Figure 19: SPICEcore drill site near South Pole Station, Antarctica.

While good drilling progress was made during the first season, there were several operational issues that had to be addressed. Chip collection by the drill was less than expected, resulting in 3-4 chip bailing runs having to be done each day. It was theorized this was due to fine chips being lost out of the drilled holes in the chips chamber as the drill was brought to the surface. If the borehole was not kept clean, then issues with penetration and difficulty drilling full length cores was experienced. The -50°C ice was found to be very abrasive and would dull cutters quicker than experienced on past projects in warmer ice. The extreme cold temperatures also caused the cutters to chip while drilling. The ice also required higher motor torque than expected to drill. Standard cutters were modified into step cutters (Zagorodnov et al, 2005) at the South Pole Machine Shop, where each cutter only cuts 1/3 third of the kerf. This style of cutters required less torque and also reduced some of the penetration issues. Another complication in the first season arose from the drilling fluid used. Several drillers reported negative side effects after exposure to the Estisol 140 drilling fluid, despite measured vapor levels being well below published exposure limits. Side effects included mild (but prolonged) headaches, burning eyes, skin irritation, and temporary reduction in mental acuity.

During the second drilling season in 2015-2016, drilling operations were changed from two shifts to three to facilitate drilling operations 24 hours each day and also to reduce the time drillers spent exposed to the drilling fluid. In an effort to improve chip collection with the drill, the non-perforated chips chamber was used along with a modified hollow shaft. Modifications to the hollow shaft included drilling a pattern of 120, 12 mm diameter, holes through the tube and covering the shaft with an 80 mesh stainless steel filter sleeve, which allows drilling fluid to pass from the annular space in the chips chamber to the center of the hollow shaft and out back to the borehole. This configuration greatly reduced the amount of cuttings being lost to the borehole to the point only three bailing sessions were required over the entire season. All cores drilled during the first part of the season, from 736 m to 1078 meters, were put directly into HDPE sleeve netting and into the core storage trench without cutting in anticipation that the ice would be brittle. This ice was stored in the trench to relax and was shipped off continent the following season. After 1078 m, the cores were again cut into 1 meter lengths, bagged and packaged into insulated boxes for transport back to the U.S. Drilling continued to a final depth of 1751 m, as additional cable was available on the winch drum. A total of 1015 meters were drilled during the second and final season over a 50-day period. Drilling progress for the entire SPICEcore project is shown in **Figure 20**.

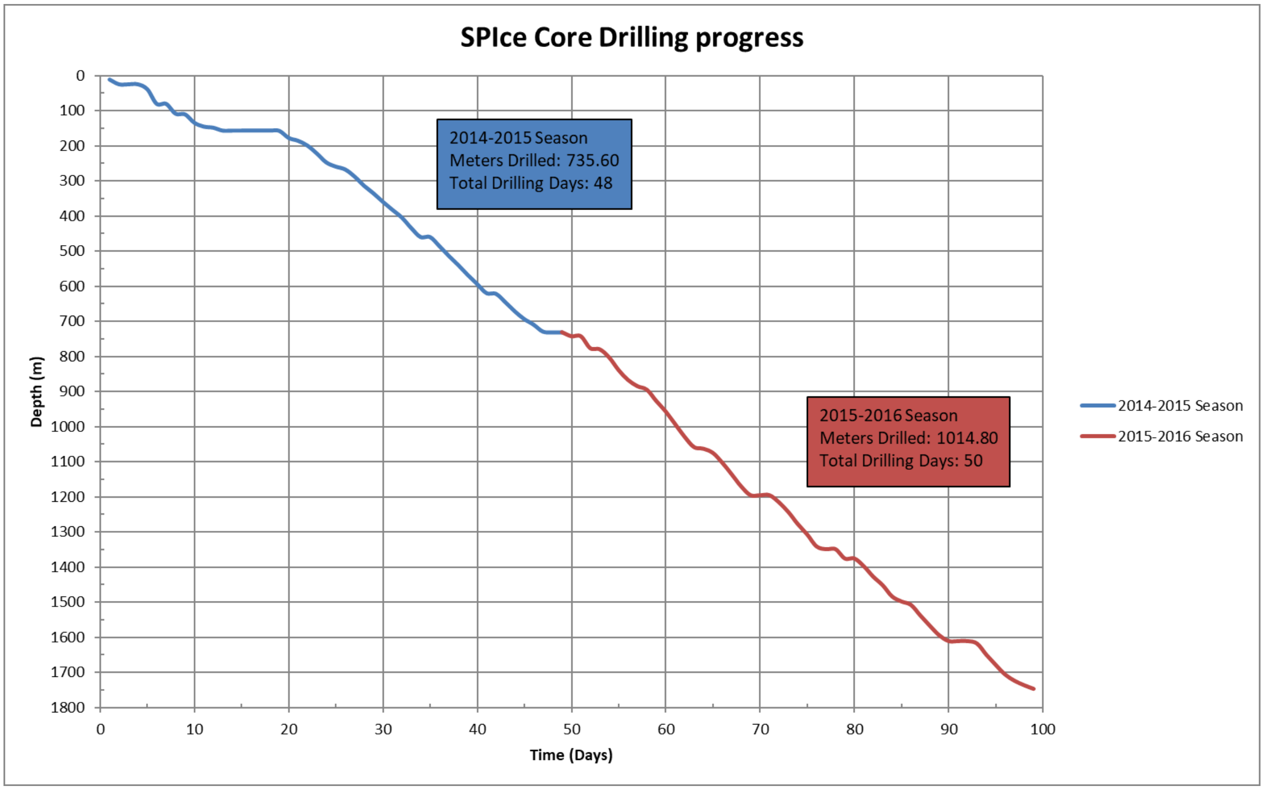

Figure 20: SPICEcore project drilling progress.

Step cutters, visible in Error! Reference source not found., were used exclusively until drilling neared 900 m depth and the drill began experiencing penetration issues. Drill penetration was not an issue when the full width kerf cutters were re-installed. From approximately 1200 m onward, the remaining drilling was done with full width kerf cutters. Motor current continued to be higher with this style of cutters, but it resolved penetration issues. IDP has yet to understand why the step cutters worked well for a period of drilling and then began to experience penetration issues. Prior to the second season, all cutters, which were made from A2 tool steel, were re-heat treated with an additional cryogenic processing step. This refined the materials grain structure and improved the toughness and resolved the chipping issues experienced the first season. Negative side effects from exposure to the drilling fluid were still experienced the second season, but to a lesser extent. IDP attributes this to the shorter shift lengths and the greatly reduced amount of bailing that had to be done, which is an inherently messy process and exposes the operators to greater amounts of drilling fluid. The final days of the second season were spent starting disassembly and packing of the drill system. The casing was extended up to the trench floor level, and the slot was filled in.

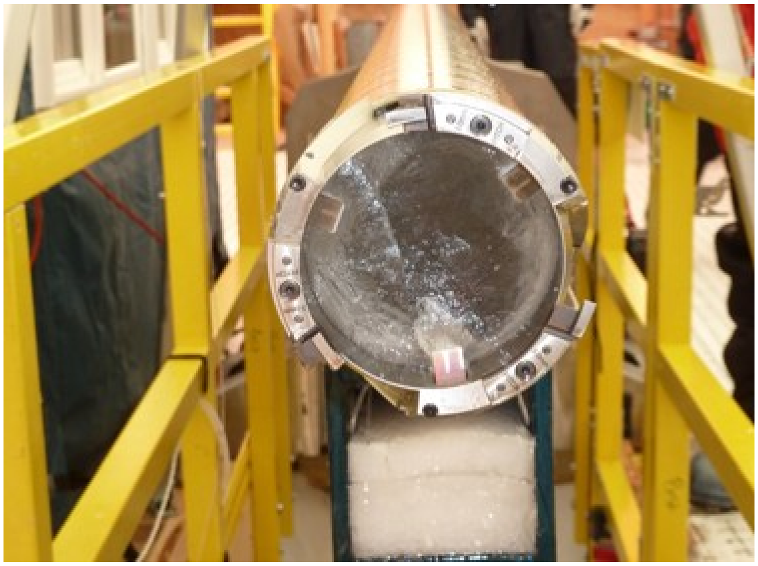

Figure 21: Step cutters on the Foro 1650 core barrel.

The third and final field season, which took place from November 23, 2015 to December 13, 2015, focused on packing and shipping the remaining ice cores, conducting borehole logging, packing the remaining drilling equipment and decommissioning the drill site. The remaining 614 meters of ice were processed for shipment back to the U.S., which included cutting and boxing all of the brittle ice that had been relaxing over winter. A total of five logging runs were completed, which included one video log, two temperature logs, and two laser dust logs. Once the logging was complete, the remaining drill system components, including the core processing line and tent, were packed and all equipment was shipped off continent. The casing was extended to above surface level and the drill trench was backfilled.

7.2.2.3 Foro 3000 Deep Ice Coring Drill

In order to recover ice cores from sites that are deeper than 1650 meter and up to depths of up to 3000 meters, the Foro 3000 Drill is being constructed; a model of the drill system layout is shown in **Figure 22**. This drill system features a larger winch, with 3100 meter capacity of 7.2 mm diameter four-conductor cable. The winch will be located beyond the end of the drill tower due to its larger size. A new tower base has been designed that pivots with a dual arm linkage so that the drill will remain stationary as the tower tilts, as seen in **Figure 23**. The drill utilizes the Foro 1650 (a.k.a IDD) anti-torque and motor sections mated to a longer chips chamber and core barrel for recovery of 3-meter cores per run. A new instrument section electronics package is also in development that will include pressure and temperature sensors, inclination, and anti-torque slip detection using an accelerometer. The system will also include a custom-built DC to DC converter and integrate an off-the-shelf motor controller that will drive a brushless DC motor. The remaining components of the Foro 1650 system can be used or duplicated with little or no modifications. The entire Foro 3000 Drill and core processing line is designed to fit within the Foro 1650 tent dimensions, allowing the system to be configured for intermediate depth or deep drilling with minimal additional parts.

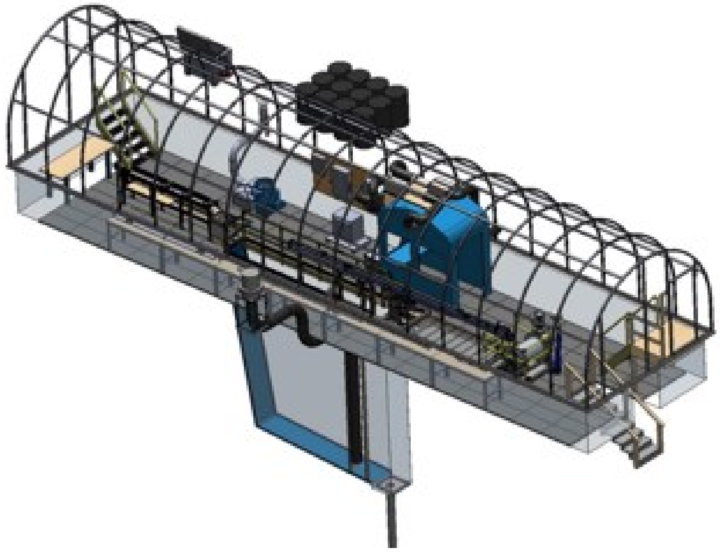

Figure 22: Foro 3000 Drill system layout.

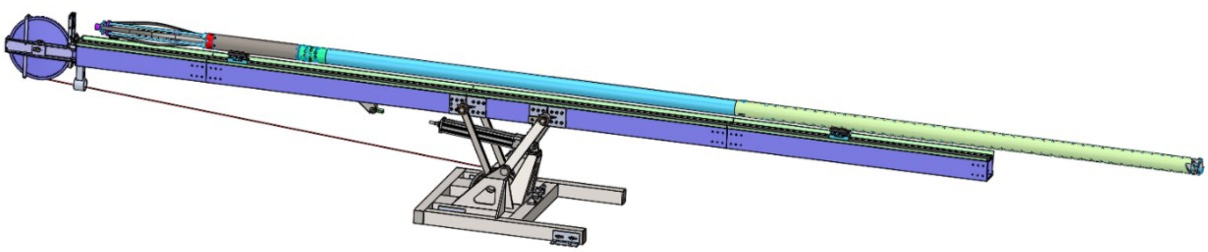

Figure 23: Foro 3000 tower design.

7.2.3 Large Diameter Ice Coring

One of the major unsolved mysteries of Earth's climate system history is the question: why did the climate system change from a dominantly 41,000 to a 100,000 year glacial cycle approximately one million years ago? Numerous research endeavors have been and will be related to this transition and earlier through ice core records dating back to over a million years ago. There are two very different drilling approaches to retrieving ice this old; the first is to target a location where the ice has been subject to minimal ice flow, which requires coring through thousands of meters of ice. The second way is to find very old ice that, through glacial dynamics, has undergone flow and is now found at fairly shallow locations. Because the chemical evidence within the ice requires significant samples of ice, use of a large diameter ice coring drill in the shallow locations facilitates retrieval of larger volumes of ice. In 2009, the U.S. Ice Drilling Program developed a large-diameter drill for use in blue ice areas of Antarctica, and the large-diameter drill was called the Blue Ice Drill (BID).

7.2.3.1 Science Requirements of the Blue Ice Drill

The original Scientific Requirements for the Blue Ice Drill were:

- Ideal ice core diameter of 24.13 cm (acceptable range 22.86 - 24.77 cm) or 9.50 in. (acceptable range 9.00 - 9.75 in.)
- Minimum core length of 1.0 m
- Maximum core length of 1.6 m

- Core quality shall be such that the total surface area-volume ratio of 10 linear meters of consecutively drilled 24.13 cm diameter core does not exceed 21 m^2/m^3. This sets an upper bound on the number of breaks or fractures of the core.
- Samples must be free of contamination from oils, greases, exhaust fumes and any carbon-containing lubricants or fluids
- Drill system must be capable of reaching depths of at least 12 m
- Core to be collected with an angle of deviation less than 10° from vertical.
- Drill shall be capable of producing a minimum of 7 sample cores per day. Note: For each hole, the top 5 meters of ice will be augered or drilled and discarded. Sample core will then be drilled from this depth.
- Drill components shall be such that the entire drill system is transportable by one helicopter load. System design shall be based on the load capacity of a Bell 212 helicopter or similar (exact dimensions TBD).
- All components shall fit inside the helicopter
- The optimum drill system weight is no more than 200 kg (440 lbs), and the maximum weight should not exceed 500 kg (1100 lbs)
- Individual drill components shall be of a size and weight that they are moveable by 1-2 people

7.2.3.2 Blue Ice Drill Design

The Blue Ice Drill (BID) leverages design features of numerous existing electromechanical ice-coring drills, consisting of a double barrel coring assembly with a cutter head and a motor/reducer section (Kuhl and others, 2014). It currently has two configurations, one for shallow drilling to approximately 30 m depth and another version for core collection to 200 m. In the shallow version, an operator uses a T-handle to anti-torque the drill from the surface. The 200 m version is referred to as the BID-Deep. The drill assembly is supported by a 5.3 m aluminum tripod with dual sheaves on top. Ropes are used during shallow coring to raise and lower the drill string. The BID design incorporates an optional core recovery tool (CRT) to help break the core if needed. If cores are drilled without core dogs installed, or if the core dogs fail to successfully capture the core, the drill can be brought to the surface and the CRT barrel lowered over the core. The CRT induces a core break by tipping the core to the side, similar to a device designed and implemented by CRREL for an even larger 12-inch diameter drill in the 1980's [Rand and Mellor, 1985]. **Figure 24** shows the original BID system components.

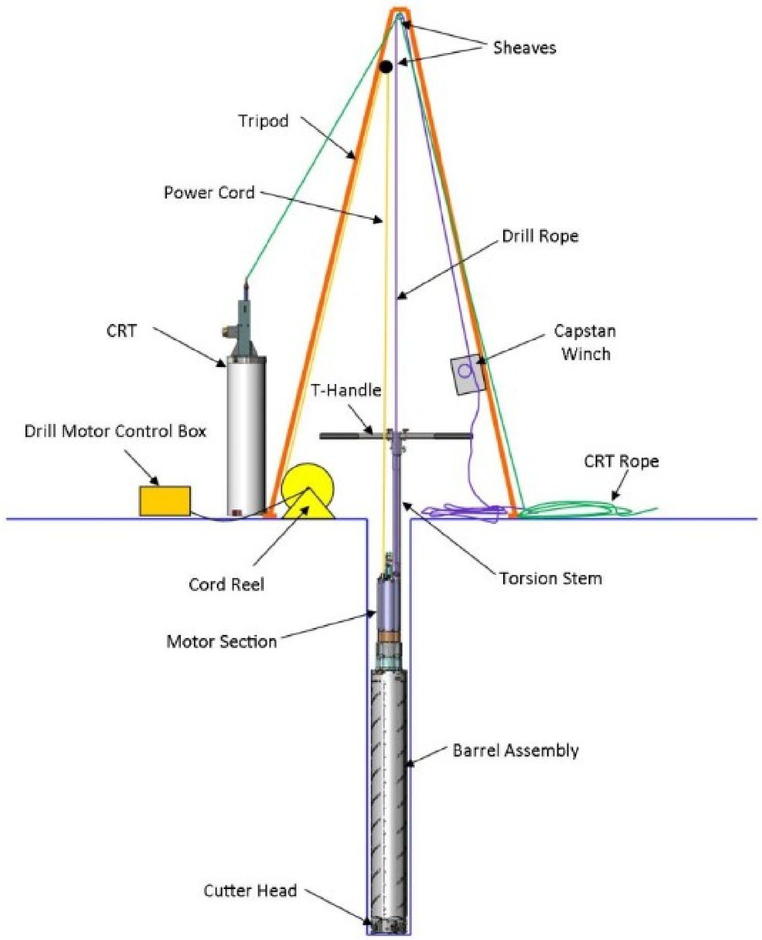

Figure 24: Original Blue Ice Drill components.

7.2.3.3 Performance of the BID

Performance values for the original BID system are summarized in **Table 3** as follows:

Table 3: Performance of the BID system

Cutting Pitch (depth per revolution)	15 mm (5 mm depth of cut per cutter)
Rotational Speed	60 RPM (cutter head)
Weight on Bit (WOB)	Minimum possible (negative WOB ideal)
Drill Motor Power	0.5 kW typical (1.5 kW max) while coring
Core Length (max repeatable)	1.15 meters
Core Quality	1 piece cores, excellent surface finish in crack-free ice
Coring Rate	1 meter per minute
Core Production Rate (maximum)	60 meters per 10 hour shift (2 holes in close proximity)
Hole Depth (maximum)	30 meters
Hole Inclination (measured)	< 0.5°
Contamination	None identified
System Weight (including complete spares and tent)	1580 kg (500 kg with minimal equipment)

A custom stainless steel cutter head holds three cutters made of hardened tool steel. Cutters are spaced 120° apart, have a 30° rake angle and a 7° clearance angle from horizontal. The cutter head is shown in **Figure 25**. Both thin kerf (241 mm core, 288 mm hole) and wide kerf (240 mm core, 291mm hole) cutters are available. Carbide cutter tips are available for drilling in dirty ice regions. Penetration shoes of various sizes may be implemented to control the depth per cut/penetration rate. Finally, the cutter head contains six spring-loaded core dogs also made from hardened tool steel. Three different lengths are available to adjust for varying ice conditions. During coring, the core dogs remain retracted into the cutter head, but engage the core when coring is completed and the operator pulls up on the drill string. This action fractures the core from the ice sheet and also holds the base of the core while the drill is brought to the surface.

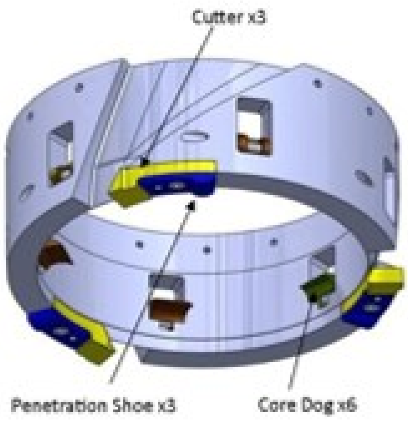

Figure 25. BID cutter head.

Common to many ice coring drill designs, the BID incorporates a stationary outer barrel with a rotating inner barrel. The core barrel for this drill is made of fiberglass tubing, which is readily available and provides for a strong, round, straight, and lightweight core barrel. The outer barrel is painted white to reduce solar gain. Three helical flights are wrapped around the outside of the inner barrel, as shown in **Figure 26**. Chips are transported upward by the rotation of the helical flights inside the outer barrel, where they then enter the interior of the core barrel through three small windows. The chips then accumulate on top of the ice core. An optional plastic plug can be installed before drill descent to separate the core from the chips if desired.

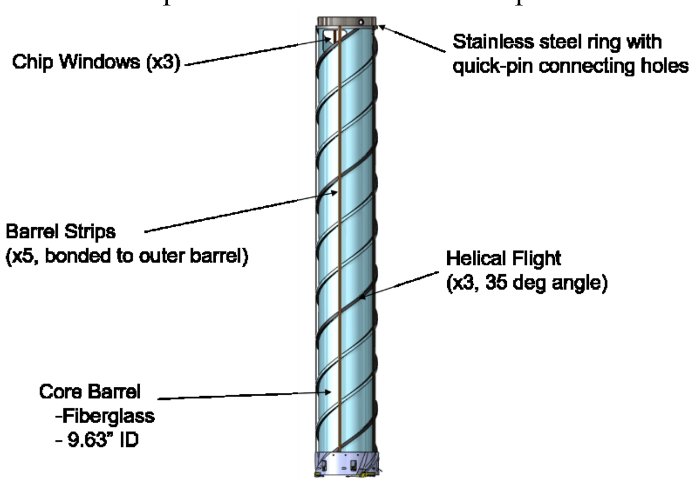

Figure 26. BID core barrel.

The BID utilizes a custom 1.9 kW AC induction motor capable of 1730 rpm. A planetary gear reducer (28:1) provides for a 60 rpm cutter speed. An aluminum and stainless steel housing encloses the motor and reducer components as shown in **Figure 27**. Versions of the motor section are available both with and without a load-triggered slide hammer to assist in core break. Up to six neodymium magnets can be added or removed to adjust the actuation force of the slide hammer. The slide hammer can repeatedly produce clean core breaks. Two versions of the motor section exist. The version of the motor section without a slide hammer is shorter and lighter, and is used with the CRT.

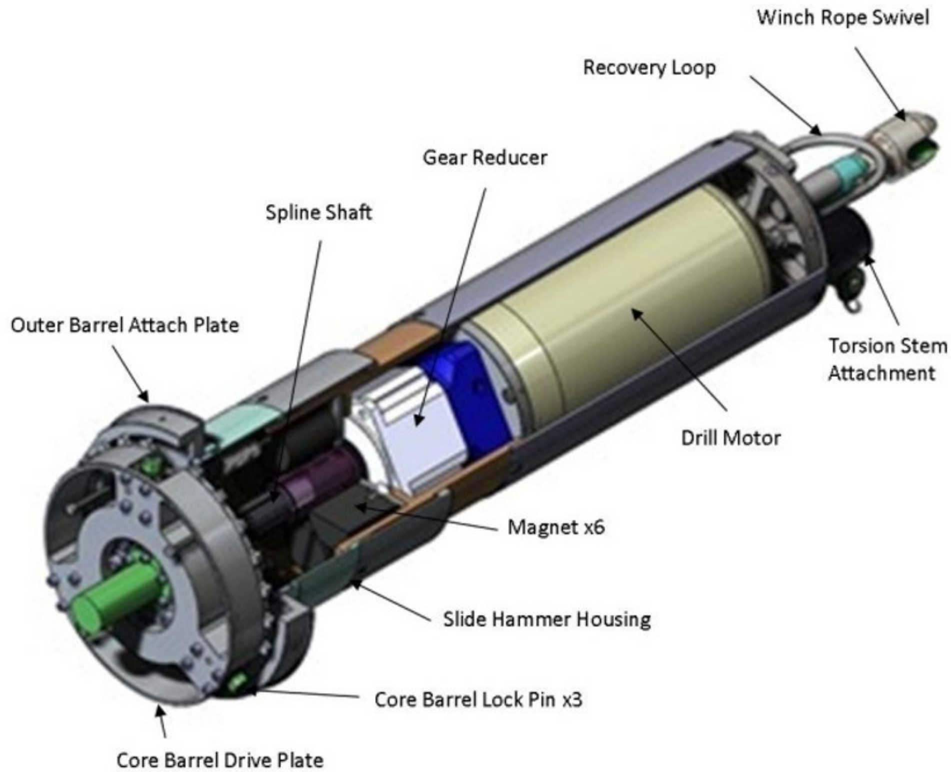

Figure 27. BID motor section.

The CRT consists of a 1 m long fiberglass tube with three core dogs at the bottom. The top of the CRT is illustrated in **Figure 28**. As described in [Kuhl et al, 2014] a tilt mechanism, illustrated in **Figure 29** is attached to the top of the core barrel with three bayonet-style lock-pins. The tilt mechanism transforms a vertical force from the suspending rope to a horizontal force via a cam profile/follower actuating a spring-loaded piston. A vertical force of 700 N is sufficient to actuate the tilt mechanism, breaking the core at the base. The core dogs engage in the core to resist the vertical actuation force and hold the core for retrieval to the surface. Use of the CRT can save time during operations by being deployed to retrieve a previously-drilled core while the drill sonde is being cleaned and readied for the next drill run. Use of the CRT prevents operators from having to separate the inner and outer core barrels of the primary drill sonde after each coring run. This method provides efficiencies when drilling to approximately 30 m or less.

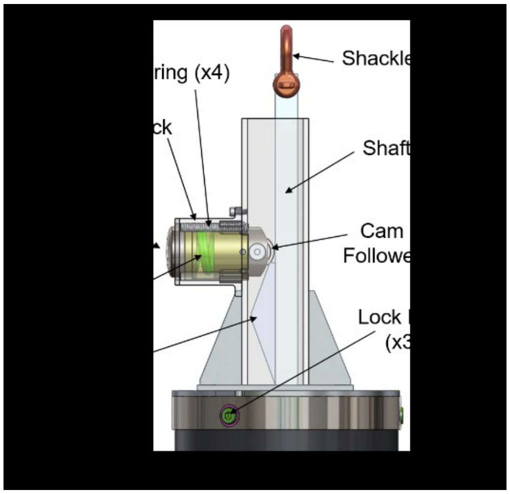

Figure 28. Top section of the BID Core Recovery Tool.

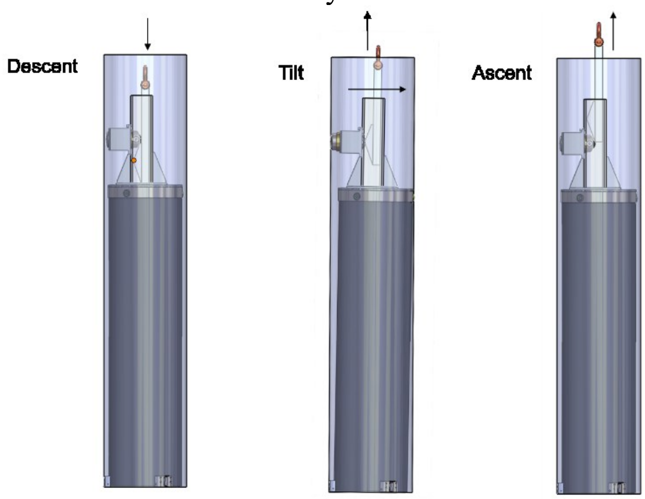

Figure 29. Core Recovery Tool tilt mechanism actuation.

Power for the BID system is provided by a single 6.5 kW generator (240 V, 20 A continuous). A custom control box and variable frequency drive convert the 240V, single-phase generator output to three-phase power to operate the drill motor. 120 V single-phase power is supplied to two outlets on the control box to power the winch motor and other components. A spring-loaded cord reel sends power down to the drill motor. The control box allows the operator to turn the drill on and off, control its speed and direction, control the variable frequency drive (VFD) settings and has an integrated emergency stop button. A small screen provides the operator with motor load data. The drill can be controlled via either the control box or via two interlock switches on the torsion stem handles during shallow coring. A schematic of the BID power and control system is shown in **Figure 30**.

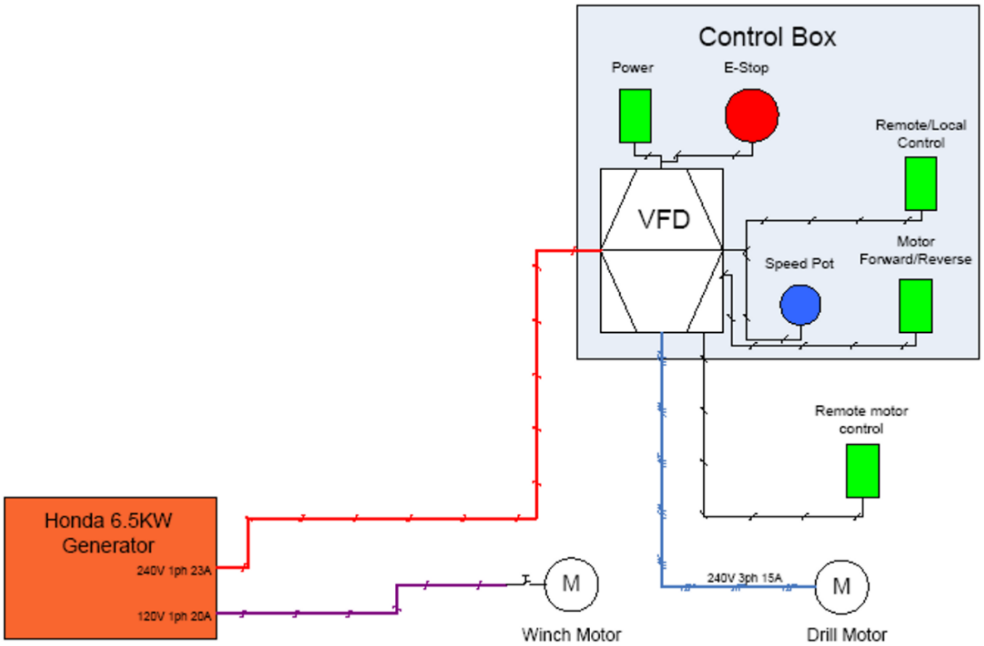

Figure 30: BID power and control system diagram. The VFD is a variable frequency drive.

The BID incorporates a 5.3 m tripod made of aluminum pipe that can be broken down for transport. The tripod can be seen in **Figure 31**. Two of the three legs can be adjusted to ensure the drill hangs plumb when set up on uneven surfaces. Two sheaves mounted on top of the tripod allow for both the drill and CRT ropes to remain installed and ready for use. A capstan winch attaches to one of the tripod legs and is operated by a foot switch. A custom HDPE sled is available for projects requiring numerous drill moves between holes. Due to the height of the tripod, the sled may only be used on relatively flat terrain.

Figure 31: BID tripod deployed in Taylor Valley, Antarctica.

Operation of the BID requires at least two operators. One operator controls the capstan winch for lowering and raising the drill and CRT. This operator also monitors and operates the control box. A second operator operates anti-torque handle (t-handle) attached to the core barrel or rigid extensions. Both operators perform core handling and drill cleaning tasks.

7.2.3.3.1 BID-Deep

In light of the success of the original BID design and a desire to reach deeper targets of scientific interest, the U.S. Ice Drilling Program designed and implemented a number of modifications and upgrades to extend the system's depth capability to 200 m. A cable winch was integrated with one of the tripod legs along with a steel electromechanical cable (9.6 mm diameter). The winch utilizes a 4 kW motor with a 119:1 gear reducer. Anti-torque blades were added to the motor section, to provide downhole anti-torquing capability. To accommodate the bend radius of the new steel cable, a larger sheave was implemented on top of the tripod. The BID-Deep is powered by a single 6.5 kW generator. Tie rods are used to join the three tripod legs to increase its load capacity. Improvements to the magnetic slide hammer were also made. **Figure 32** shows a schematic of the BID-Deep components.

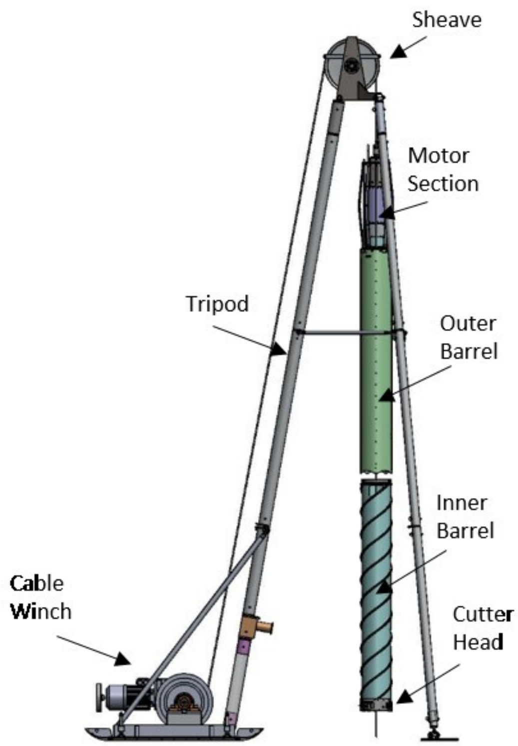

Figure 32: Model of the BID-Deep system.

A weather-tight hand-held operator's pendant, connected to the winch via a power cable, allows the winch operator to control both speed and direction of the winch. A hand wheel is also available for finer BID-Deep drill position control. Two emergency stop buttons are incorporated, with one on the pendant and one on the winch itself.

7.2.3.3.2 BID Drill Tent

Due to the height of the BID system, an existing tent design was not found that could accommodate the BID. In an effort to maintain operations during inclement weather, IDP worked with Fabricon LLC in Missoula, MT; the custom tent is shown in **Figure 33**. The tent was designed to sustain wind gusts up to 50 knots or 20 psf of snow load. The tent attaches to the BID tripod via a ring mounted near the top of the drill tripod. A pipe frame forms two door arches on either end of the tent as well as provides support for the main arch. Guy ropes are used to secure the tent. White WeatherMax80 nylon fabric helps reduce solar gain inside the tent during drilling operations. The drill tent proved invaluable during its first field use at Law Dome during the 2018-2019 Antarctic field season. A similar tent is currently being constructed by Fabricon LLC for use with IDP's Foro 400 Drill.

Figure 33: BID drill tent in use at Law Dome, Antarctica.

7.2.3.3.3 Cleanliness Requirements

Because the large-diameter ice cores collected by the BID are traditionally melted immediately in the field to capture gases contained in the ice, projects utilizing the BID thus far have required a cleanliness protocol be implemented to ensure the drill is free of contaminants and, historically, to ensure carbon-free sampling. The following describes the pre-shipping cleaning protocol implemented by IDP, as outlined in the BID Operations and Maintenance Manual.

- Metal parts that come in direct contact with the core (coring heads, cutters, dogs, CRT dogs and holders, hardware for all, mango carabiners and rings, etc.) undergo ultrasonic cleaning in acetone, then 190-200 proof ethanol, then DI water.
- Fiberglass and plastic parts (core barrels, outer barrels, CRT Barrel, mangoes, CRT unloading ring, etc.) are scrubbed with ethanol, rinsed with DI water, air dried overnight, and then wrapped in large lay-flat tubing.
- Metal parts are baked at 50°C overnight in a Tenney environmental chamber. Non-stainless steel parts are rinsed with DI water just before insertion into the Tenney chamber to minimize rust.
- Clean small parts are packed in clean plastic parts organizers or new plastic Ziploc bags. Coring heads and other large clean parts can be wrapped in large layflat tubing.
- Plastic organizers must be cleaned before putting in clean parts if they are new or were contaminated during a previous season. Ethanol and DI water are used for this application.
- The remainder of the sonde(s) is wiped down with ethanol to degrease it before being packed. Anything that goes downhole should be degreased.
- Clean coring heads are reassembled and the heads, barrel sets and CRT barrels and core dog mounts are then wrapped in layflat tubing and packed into cases.
- Approximately 4 gallons each of Acetone and 190-200 proof ethanol are needed for the cleaning process.

7.2.3.3.4 Performance Experience

The BID can quickly produce large amounts of core during a single field season. The BID was first used in Taylor Valley, Antarctica during the 2010-2011 field season where approximately 575 m of ice were drilled. The drill has deployed regularly for several Arctic and Antarctic field seasons. Production rates as high as 1200-1400 m have been achieved during a 6-8 week long field season.

The BID-Deep system was first tested in Greenland during the 2014 Arctic field season, reaching a depth of 187 meters (approximately 80 m of firn and the rest ice). The BID-Deep capabilities were further tested in Taylor Valley in Antarctica during the 2014-2015 field season down to a depth of 70 meters in a blue ice area with almost no firn. The drill system has since been used in both the Arctic and Antarctic in both blue ice areas and areas with overlying firn. In the majority of projects, deterioration of core quality was observed approximately 70 meters below the firn-ice transition, or 70 meters below the surface in blue ice areas. Core quality was very poor with severe fracturing resulting in cores made up of 3 to 10 pieces per meter. Numerous combinations of drill parts and drilling techniques were tried with no noticeable improvement. Depth capability is largely influenced by site/ice characteristics. The current equipment is likely reaching its design limits; ensuring good quality core collection to depths of 200 m would require a re-design of the system.

7.2.3.3.5 Modifications

In an attempt to improve core quality at depth, IDP engineers surmise that the fiberglass core barrel may not be sufficiently rigid for deeper drilling, because the fiberglass may be inducing flex and breakage in the cores. A carbon fiber core barrel has been designed and the barrel will be tested in Antarctica during the 2019-2020 field season.

During the first use of the drill tent with the BID during the 2018-2019 Antarctic season, IDP engineers determined that use of the tent requires a stronger support structure than the BID tripod, as well as a simpler, safer erection method. To this end, IDP engineers have designed a new truss-style tower, floating base and new sheaves for use with the BID-Deep. The new designs will be tested the Antarctic 2019-2020 field season. The tripod may still be used for shallow coring configurations without the tent.

7.3 Coring Ice-Rock Composites

The demise of glaciers and ice sheets under current climate change, with accompanying rise in sea level, has created urgent scientific questions about the extent of ice sheets during the previous interglacial period. Cosmogenic nuclides in bedrock beneath ice sheets reveal clues to the former extent of ice sheets and the timing and duration of past exposure periods. Several innovative technologies for retrieving bedrock core from beneath hundreds of meters of glacial ice using nimble methods have been developed and used by the U.S. Ice Drilling Program. Designed for reconnaissance recovery of short rock cores for cosmogenic nuclide techniques to quantify periods of exposure (ice free) and burial (ice cover), the Agile Sub-Ice Geological Drill (ASIG) and the ice-adapted Winkie Drill are useful for retrieving meters of bedrock core near glacial rock outcrops and near the ice sheet margins.

7.3.1 Agile Sub-Ice Geological Drill

Under ice less than 700m thick, nimble methods for reconnaissance recovery of small rock cores are needed for use near outcrops and near the ice margins. The U.S. Ice Drilling Program organized iterative discussions between scientists and the IDP-Wisconsin engineering staff in order to create the following IDP Science Requirements for the Agile Sub-Ice Geological Drill:

- Produce 700 m borehole to base of ice with drilling and retrieval of 10 m of bedrock core and / or unconsolidated frozen sediment core.
- Ice drilling will include the possibility that the ice is entrained with rocks.
- Ice drilling will be to dry, frozen-bed conditions, and will not be done in areas where there is subglacial water.
- Retrieve several short ice cores (~50 cm long) at up to 700 m depth.
- Ice drilling may be in ice that is within 2.0°C of the pressure melting point.

- Required ability to drill at ice borehole temperatures as low as -40°C, and surface temperatures as low as -30°C.
- Retrieve 10 m of bedrock cores of maximum 33 mm (1.3”) diameter beneath the ice sheet.
- Maximum site altitude for the design should be 2,500 m.
- Maximum time at a site, including set up and core retrieval, should be 6 days.
- Stand-alone capability is needed for operation at small field camps at remote sites.
- Minimal staff (4) for drilling operations in the field; other field camp staff in support of drilling operations to be provided separately.
- Drilling fluid or a fluid “system” (to be determined) will be immiscible with water.
- Drilling fluid should not be a boron-rich fluid.
- Drill system must be transportable by Twin Otter aircraft, or helicopter with sling load.
- Drilling depth of each core collected should be determined and recorded.
- Drilling and core handling history should be recorded.

The Agile Sub-Ice Geological Drill (ASIG) Drill is the first drill with the capability of retrieving meters of rock from under hundreds of meters of ice. The drill system design is based on a commercially-available conventional drilling rig with rod extensions, as commonly used for minerals exploration, which IDP has adapted for drilling through ice and for ice coring. The system is designed to drill access holes through ice less than 700 meters thick and subsequently collect meters of bedrock cores from beneath glaciers.

7.3.1.1 System Overview

The ASIG Drill system uses a modified version of the Discovery MP1000-Man Portable Core Drill Rig from Multipower Products Ltd; the schematic is shown in **Figure 34**. The system is designed to be field-portable by Twin Otter aircraft for example, as illustrated in **Figure 35**. Specifications for the system are provided in **Table 4**. Permeable layers are cased and sealed to impermeable ice with an inflatable packer. The system uses industry-standard downhole tools with minimal modification. Ice is drilled in a continuous manner with a full-hole bit to create an access hole. Traditional rock coring equipment and techniques are used for sub-glacial rock sampling. Custom and off-the-shelf rock coring bits compliment the ice drilling bits to core ice, rock and transitional ice layers containing sediment; the drill bits, which require continuously-circulated drilling fluid, are depicted in **Figure 36**.

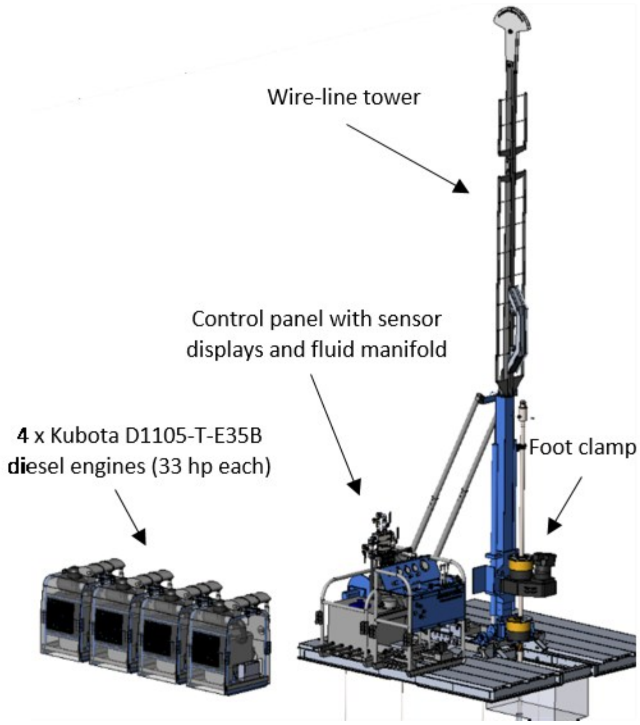

Figure 34: As-built CAD illustration of the ASIG Drill Rig.

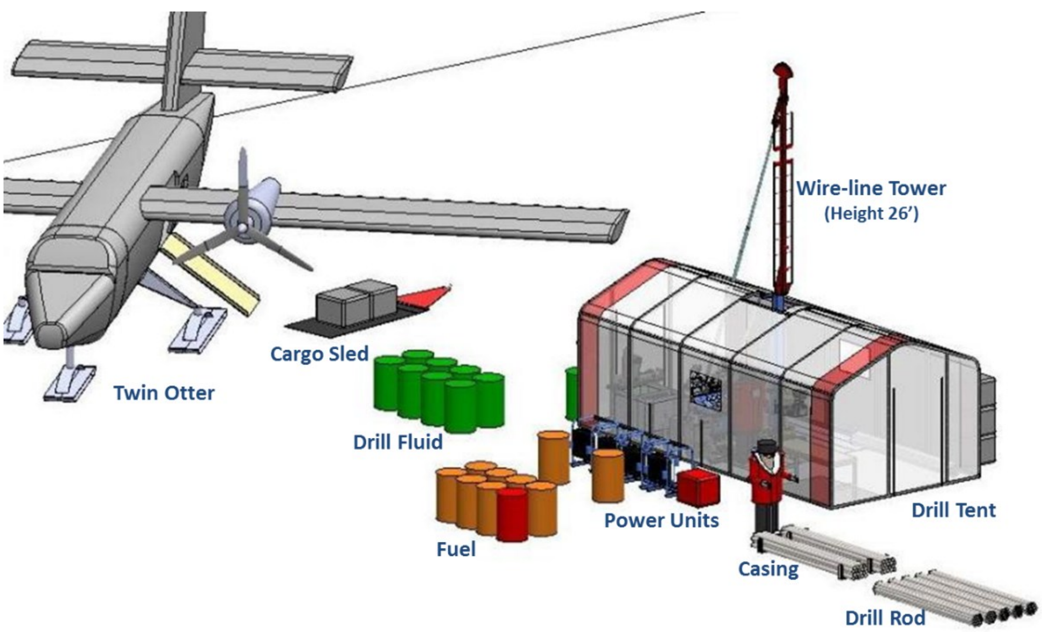

Figure 35: Schematic of a typical AISG drill site (Gibson et al., 2015).

Table 4: IDP ASIG Drill System Specifications

Drill Type	Surface Driven Rock Coring Rig

Power Unit	4ct. Kubota D1105-T-E35B Diesel Engines (33 hp each)
Drill String	Rigid, Single Wall Drill Rod (Sandvik WL56)
Rod Tripping Mechanism	Rig mast hydraulics/chuck
Drill Fluid	Isopar K (Exxon-Mobil)
Fluid Filtration	Continuous - shaker table, secondary filter, chip melter
Rod/Core Barrel Configuration	Sandvik WL56 thin-kerf metric
Core Size [mm]	39 (larger core possible with different drill rod)
Maximum Core Length [m]	1.5 or 3.0
Available Bit Configuration	Hardened Steel (ice), Diamond-impregnated, GeoSet, PDC
Depth Capacity [m]	700 (~1500m max with modifications, needs testing)
Drill Rod Material	Steel
Rod Weight [kg/m]	3.8 (for 39mm core)

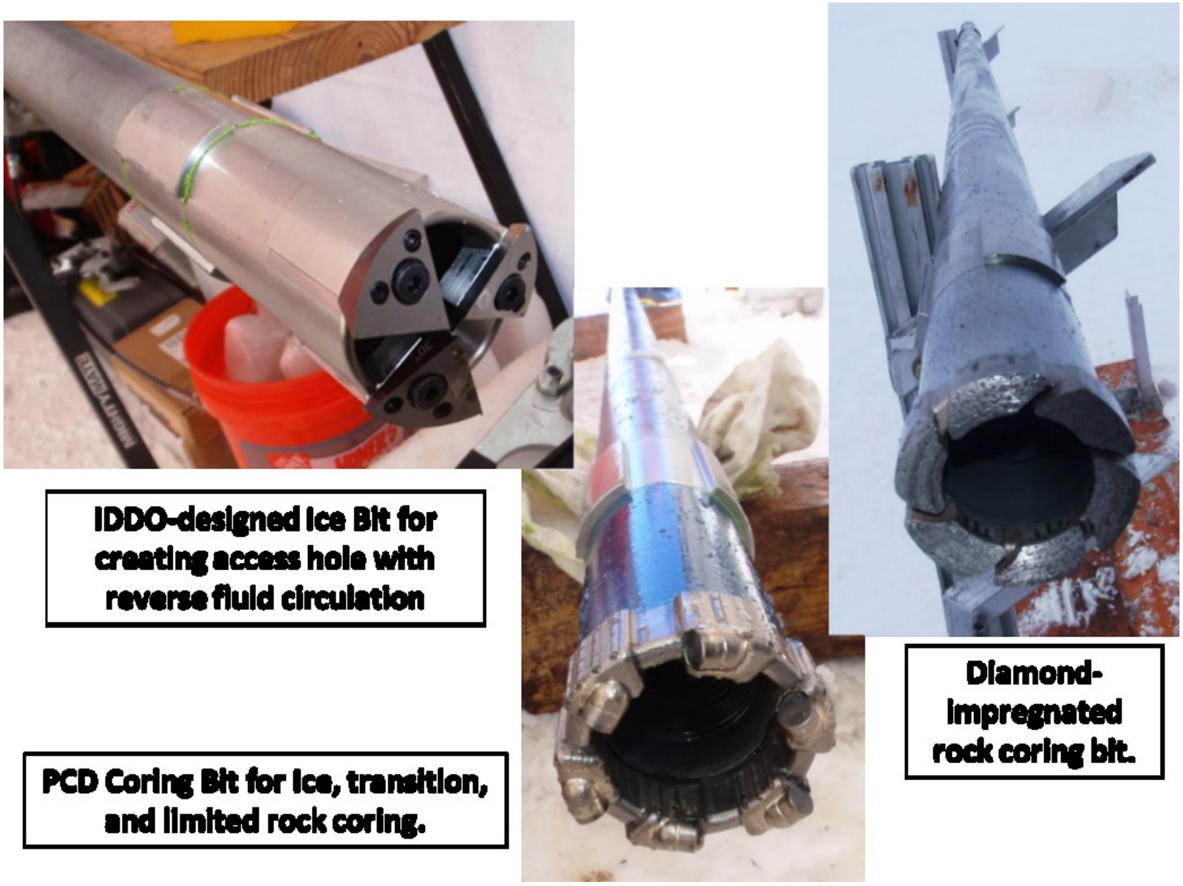

Figure 36: Drill bits for ice, rock and mixed media in transition zones.

Rigid pipe is used when cutting chips, creating an access hole and when drilling ice and rock core. For ice and rock core collection, a wireline recovery system using the Sandvik WL56 core barrel assembly is deployed down the center of the drill pipe. This method greatly reduces cycle-time as compared to removing the rigid pipe drill string to recover core. After the casing is set, continuous drill fluid circulation and chip filtration is maintained by a positive displacement piston pump and a custom filtration system. Drilling fluid is continuously recycled during drilling and the vast majority of the drill fluid can be recovered at project completion and reused. Circulation pressures can be more than 100 psi (0.69 MPa), so it is critical that drilling be performed in competent ice in an environment with a frozen bed. Reverse circulation is used for cutting chips and creating an access hole and normal or forward circulation is used when a core has been collected. Adaptation of the system for use in environments with an aqueous ice-rock interface is conceptually possible and would require additional engineering development.

7.3.1.2 Logistics

To address the need to deploy the system to remote sites, the system is designed to be useful with minimal deep field logistics to be transported via light fixed-wing aircraft, helicopter, or tractor traverse. Heavy equipment is not required for assembly at the field site. When heavy equipment is available, however, it does speed operations in set-up, tear-down and transport between holes. All of the ASIG Drill system equipment is limited to a 600 lbs. max single-piece weight. Total weight of the system is highly dependent upon project requirements including, the number of holes, the depth of required casing, and total depth to bedrock; weights for two example applications are listed in **Table 5**. Spare components and extra drilling fluid are recommended, but may increase system weight significantly.

Table 5: Sample ASIG Drill system weights for shallow (200 m) and deep (700 m) projects. Weights are given in lbs. (kg).

Drill Equipment		
	200 m	**700 m**
Drill Rig lbs. (kg)	4,565 (2,070)	4,565 (2,070)
Drill Rod lbs. (kg)	1,900 (861)	6,971 (3,162)
Tools/Equipment lbs. (kg)	6,533 (2,963)	6,608 (2,997)
Total Equipment Weight lbs. (kg)	13,088 (5,936)	18,144 (8,230)
Twin Otter Flights‡	6-8	8-10
Consumables		
	200 m	**700 m**
Casing lbs. (kg)	310 (140)	310 (140)
Drill Fluid lbs. (kg)	2,749 (1,247)	7,588 (3,442)
Fuel lbs. (kg)	2,649 (1,201)	4,013 (1,820)
Total Consumables Weight lbs. (kg)	5,708 (2,589)	11,911 (5,403)
# Twin Otter Flights‡	3-4	6-8
Total		
Total System Weight lbs. (kg)	18,796 (8,526)	30,055 (13,633)
Total # Twin Otter Flights‡	9-12	14-18

‡Note: Number of flights based on a 250 nautical mile flight and the standard fuel capacity with no optional cabin auxiliary tank. Actual cargo capacity will vary with specific conditions and the amount of fuel required.

The approximate required time on-site for drilling operations is estimated as follows:

- 200-meter hole with 10 m core recovery = 100 working hours (4-5 people)
- 700-meter hole with 10 m core recovery = 150 working hours (4-5 people)

These are approximate values. In practice, large casing depths, drilling problems, mechanical issues, adverse weather, etc. may significantly increase hours to completion and would need to be included in planning estimates. Also useful in planning estimates is a breakdown of drilling times for specific activities, as provided in **Table 6**.

Table 6: ASIG Drill System Performance and Operation Values

Number of Operators	3 drillers, 1-2 core handlers
Initial System Assembly (hours)	30
Time-to-Depth (200 m, 10 m core, hours)	50
Time-to-Depth (700 m, 10 m core, hours,)	100 (estimated)

Pilot Hole (auger, casing, m/hr)	10
Access Hole Drilling, total (m/hr)	8
Coring, total (m/hr)	1
Auger max. ROP (firn, m/min)	1
Ice max. ROP (full hole, m/min)	1
Rock max. ROP (coring, m/min)	0.15
System Disassembly/packing (hours)	20

7.3.1.3 Field Deployment

The ASIG Drill system was tested in a 50 ft. ice test well at the University of Wisconsin-Madison in February, 2016. From November 2016 to January 2017, the drill system was successfully deployed to remote west Antarctica near the Pirrit Hills in support of the Ex-Probe science project. Drillers used the ASIG system to drill through approximately 150 meters of ice and then collected 8 meters of 39 mm diameter rock core of excellent quality. Nearly 5 meters of ice core of poor quality was also collected near the ice-bedrock transition.

Two holes were attempted in this initial field season. In the first hole, a casing was set with the inflatable packer and drilling continued to approximately 90 m of ice. At that depth, a fracture of the ice formation occurred and drill fluid pressure was lost, stopping circulation and forcing a halt to drilling. The drill was disassembled and transported to the second site.

At the second site, the drill was reassembled, casing was set and drilling continued to the target ice depth of approximately 150 m. By pulling the drill string and changing to appropriate coring bits, 5 m of basal ice and 8 m of granite core were recovered. Core breaks in the granite were achieved through use of a collet and pulling power of the drill rig. **Figure 37** is a photograph of the drill rig in operation within the drill tent. The first successful retrieval of meter-scale rock core from beneath glacial ice is shown in **Figure 38**.

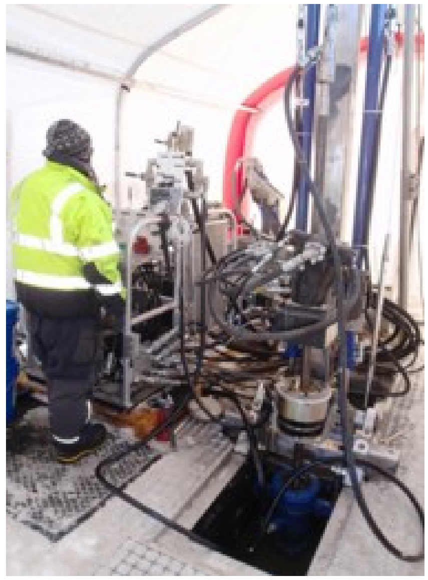

Figure 37: Drilling with the ASIG in the drill tent at Pirrit Hills, Antarctica.

Figure 38: The first subglacial rock core drilled using the ASIG Drill system. Core breaks are performed using a collet inside of the drill head.

7.3.1.4 Future Work

Based on experiences of the first field season of drilling with the ASIG drill, a number of system modifications have been identified to simplify operations and improve performance. Several modifications may significantly reduce the time required to set casing. Casing must be set at a depth beneath the firn-ice transition depth where impermeable ice is adequate to support the packer and fluid pressures. In order to determine the appropriate packer depth, it is helpful to collect ice cores and measure their density. To this end, new augers with a central clearance hole will be implemented to rapidly create the casing pilot hole and facilitate ice core sampling. Coring tools will be developed to quickly collect the ice core through the auger using the existing wireline core recovery equipment. As a compliment to the pilot hole augers, a wireline bailer system will be developed to remove cuttings left behind after the augers are removed from the pilot hole.

By improving cycle time for drilling the main ice access hole and retrieving ice core, the potential exists to significantly decrease time in the field. By modifying the foot clamp, a wider range of tools can be accommodated without disassembling the equipment. A piston driven foot clamp will be installed accommodating tools up to nearly 6 inches in diameter. This will accommodate drill rod, casing, augers, reamers and all drill bits.

The existing filtration system used a screw press to remove ice chips from the drill fluid. This required significant maintenance, demanding the attention of a third person during drilling. To reduce the need for this effort, a shaker table will be installed that is potentially maintenance free. After the bulk of fluid is removed, a melter tank using waste heat from the hydraulic power packs proved very useful in recovering the remaining fluid in the first field season. This melter tank will be enhanced for efficiency and ease of operation. Fluid recovery will be further improved by additional splash guards during all drill operations. These not only minimize losses but also improve cleanliness of the drill site.

In addition to improvements to filtration, the drill fluid circulation system will be enhanced to improve drilling fluid pressure monitoring and control. A pressure accumulator, Flexicraft MHY1650500, will be added to the outlet of the pump to dampen pressure spikes and improve stability of the gauge reading. A high precision pressure relief valve, Sun RPGE-LEN, will replace the existing pop-off valve that exhibited an excessively large activation range of over 25 psi. A simple cartridge sieve will also be added to protect the piston pump from any foreign material.

These modifications make the ASIG Drill a capable system, although potential for further improvements remains. Continued efforts in managing drilling fluid pressures will be of particular benefit going forward. Two areas of interest in managing fluid pressures are the quantification of drill fluid pressures and acceptable limits during all stages of drilling operations, and the design of equipment to allow drilling through a wet ice-rock interface or less competent ice.

7.3.2 Ice-Adapted Winkie Drill

Many scientifically interesting areas of Greenland and Antarctica are in locations that challenge the logistical capabilities of any nation. Hence there is a large need for small, light, agile drills that can be easily transported with the drilling completed with only several drilling staff. The U.S. Ice Drilling Program has adapted a commercially-available Winkie rock drilling system from Minex, and has modified and upgraded it to add ice augering and ice coring capability for a total drilling depth of 120 meters. The resulting ice-adapted Winkie system can be transported by a Twin Otter or similar-sized aircraft.

The as-purchased Winkie system is capable of rock coring to a maximum depth of 120 m with AW34 drill rod, producing core with a diameter 33.5 mm. If smaller EW drill rods are used, the drill can reach a maximum depth of 145 m. The system uses an eight horsepower, 2-stroke, gasoline engine to power the drive head. Power from the engine is transferred through the two speed transmission before being applied to the drill rods. The system is top driven; the drill rods are screwed to the drive shaft of the drive head rather than clamped into a chuck. The drive head is lifted and pushed with a hand wheel that allows for a maximum 1.53 m stroke length. The published weight of the drive head and frame is 84 kg. However, this does not include drill rod, downhole tooling, circulation components or spares. The drill can easily be disassembled into pieces manageable by teams of two people. The drill was designed to be brought to extremely remote locations as a probing or exploration rig so man-portability is paramount to its success.

The simplicity and minimal weight of the Winkie Drill makes it an ideal solution for rock coring in the logistically difficult polar regions of the world. Several key modifications needed to be made to adapt the Winkie Drill into a useful tool for collecting subglacial samples; the gasoline engine was replaced with a more reliable electric motor, a base was built to anchor and support the rig on ice or firn, oversized drill rod and core barrels were procured, an access borehole system was developed, specialized bits were procured, and a closed circulation system was designed.

The ice-adapted Winkie Drill was first deployed to Antarctica in 2016. The rig was sent to the field with the gasoline engine that came installed from Minex. The engine performed well, but the reliability of the engine was a weak point in the system. Due to the extreme isolation of many projects proposed for the ice-adapted Winkie Drill, it was decided that the engine should be upgraded to a more reliable alternative. Winkie systems have been retrofitted with hydraulic motors by several independent operators. This option was explored but eventually ruled out due to the increased system weight and complexity. An electric motor proved to be ideal because it uses already-available electric power produced by a generator, is reliable and requires minimal auxiliary equipment, and it can be safely operated inside a drill tent.

Many motor options were explored but few could closely match the power and speed produced by the US820 gasoline engine, which is visible in **Figure 39**. The closest option available is the Evo3 brushless DC motor by Sonceboz. The motor included a fully integrated controller in a sealed housing. Additional equipment required to operate the motor includes a 3kW AC-DC rectifier and simple drive head-mounted control box. As a direct replacement for the US820 motor, the Evo3 was less powerful, however, its reliability, simplicity, and improved operator comfort justified any reduction in penetration rate. Another added benefit to the Evo3 motor is the ability to add modular gear reducers between the motor and powerhead, optimizing speed and torque for specific conditions. For example, the 2017-2018 Ong Valley project requested oversized cores consisting of a mixture of ice and rock debris. To achieve the required torque while also slowing down the surface speed, a 3:1 gear reducer was added to the assembly. The graph in **Figure 40** compares the raw torque of several gasoline engines and electric motors.

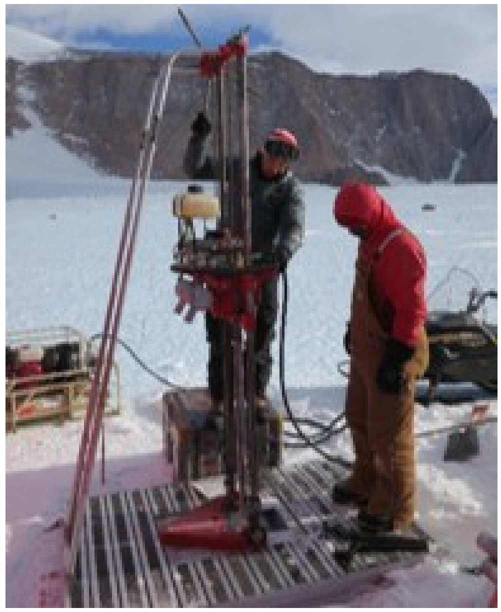

Figure 39: The Winkie Drill as operated in the Ohio Range, Antarctica. Note the gasoline engine driving the powerhead and aluminum pallet base.

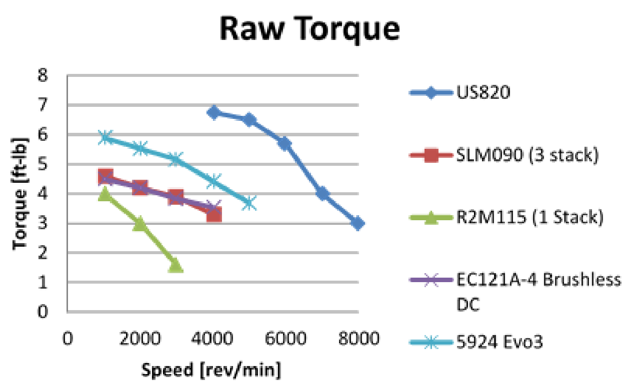

Figure 40: Comparison of the US820 gasoline engine with various electric motors.

The conventional Winkie Drill uses a small base to support the drill during operation. The base is bolted directly to the rock formation being sampled with concrete anchors. This is not an option when operating on an ice or firn surface. A custom aluminum pallet with HDPE base was fitted to the drill to distribute core break loads onto the glacial surface as well as provide a solid and safe work platform, as seen above in **Figure 39**.

The most significant capability added to the system was the ability to drill access holes through glacial ice to reach the desired subglacial samples. First implemented and tested was the use of a continuous string of augers to quickly drill through blue ice and make contact with the bedrock below. A test of the augering concept was conducted during the 2015-2016 Antarctic season at a site near Crater Hill outside of McMurdo Station. Two auger systems were tested, the 2-inch Kovacs augers proposed for use with the Winkie Drill and custom 5.75-inch augers proposed for use with the ASIG Drill. The test was beneficial in determining the power requirements for augering as well as the efficiency of the auger string at clearing the hole of chips. The 2-inch augers required much lower torque than expected; a 30 meter string could be rotated by hand even when full of chips. Even the 5.75-inch augers could be operated with the ice-enabled Winkie Drill although it has a fraction of the power of the ASIG Drill. The most significant finding of the test was the inefficiency of the augers to clear chips; chips filled between 46% and 27% of the access borehole.

The Kovacs augers were again used during the 2016-2017 field season when the ice-enabled Winkie Drill was deployed to the Ohio Range, as shown in **Figure 41.** This site was not covered in firn, rather the solid glacial ice was at the surface at this location. At this bare ice site, the augers were much more effective, leaving less than 5% of the borehole filled with chips in boreholes as deep as 28 meters. A comparison of the situations is given in **Table 7**. The huge reduction in ice chips was the result of drilling through solid ice, rather than drilling through porous firn, before reaching the underlying rock. The solid ice borehole allowed the drill string to be spun as fast as 1500 rpm to clear the chips. At sites that are covered in firn, the borehole could not support the augers at that speed; the augers would become less stable and the borehole would be enlarged as a result. Once bedrock is reached, conventional downhole tooling is utilized. A double barrel, AW34 core barrel collected rock samples at the Ohio Range.

Figure 41: At the Ohio Range, access holes were drilled in ice using Kovacs 2-inch augers.

Table 7: Ice chip depth that remained in the borehole after augering at Ohio Range were measured to determine the efficiency of the augers at each borehole.

Borehole	Borehole Depth [m]	Depth of Chips in Borehole [m]	Fill Ratio [%]
#1	26.5	0.99	3.7
#2	12.1	N/A	N/A
#3	12.9	0.55	4.3
#4	27.0	0.80	3.0

#5	28.3	1.23	4.3
#7	25.5	0.5	2.0

The next project, which was conducted during the 2017-2018 season in Ong Valley, Antarctica, involved drilling through ice-rock mixed-media and required retrieval of larger cores, so an oversized 86T2 core barrel was adapted to the drive head. Neither this nor the system used at the Ohio Range system utilized a wireline retrieval system due to the relatively shallow coring depths and limited coring runs required. For both coring systems, several bit options were deployed with the drill: diamond-impregnated, PDC, and geoset, as depicted in **Figure 42 and 44**. The most effective bit for solid rock is a diamond impregnated bit. Soft matrix bits were chosen in part because of the hard rocks predicted at the sites but also because limited core is required and generally a softer matrix produces a higher penetration rate. Maximizing the penetration rate through rock is beneficial in the case of total fluid loss drilling.

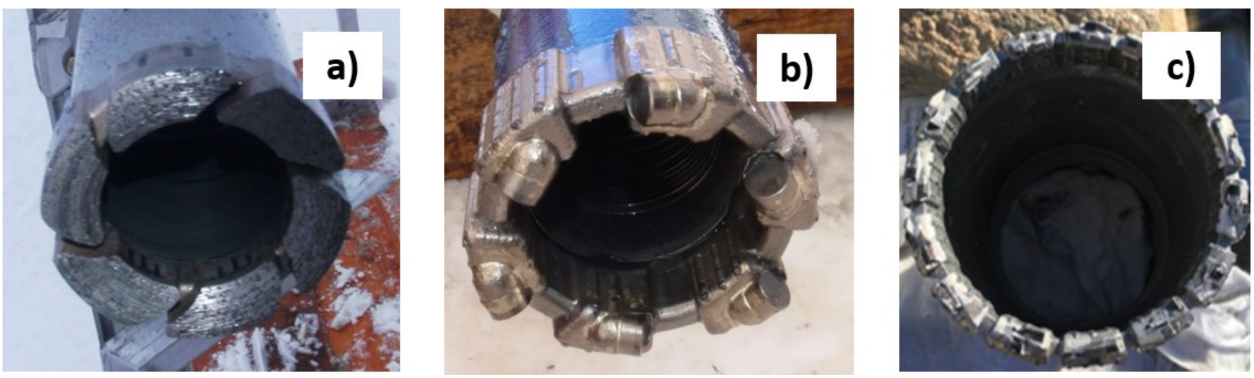

Figure 42. Photographs of the drill bits deployed for drilling mixed-media ice-rock mixture cores in Ong Valley. a) diamond-impregnated bit, b) PDC bit, c) Geoset bit.

For mixed media drilling (see rock-ice mixed media cores in **Figure 43**), it has been found that a geoset style bit (shown in **Figure 44)** is most effective. Penetration rates differed greatly depending on the media being collected but varied from 0.4 to 3.0 cm/min. The fastest penetration rates occurred in almost dry rubble and the slowest through large rocks where the full kerf was engaged. An impregnated bit is ineffective whenever ice is present at the cutting surface because the ice does not fracture with the same mechanism as rock so an ice glaze is formed over the bit and no penetration is possible. PDC bits were also tested during the Ong Valley project. A PDC bit more closely resembles a traditional ice cutting head with individual teeth that shave ice rather than crush. The PDC bit was not effective during that project, always plugging the water-ways and stopping fluid circulation. This may have been the result of insufficient fluid flow rate or insufficient annular space for chip removal.

Figure 43: Mixed media cores recovered from Ong Valley. The most effective bit for drilling this type of media was found to be a geoset style cutter.

Figure 44: This Geoset style coring bit was used exclusively in Ong Valley where only mixed media was cored.

The fluid circulation scheme is designed as a closed system, filtering Isopar K drilling fluid to remove particulates before pumping it back down the borehole. Ideally, there is very limited fluid loss, however, the cumulative effect of handling wet rods and evaporation leads to fluid loss. The mud pump recommended by Minex is a portable, gasoline powered unit. To reduce weight and minimize the number of engines running, an electric pump was instead procured. The pump was fitted with a motor drive to allow for flow rate control. The assembly uses a triplex piston pump and can produce 300 psi and a 3 gpm flow rate. A complete, spare pump is sent with the system to the field and can be added to the system to increase the flow rate if needed. The rig can operate only in forward circulation. The Ohio Range project utilized a cavity dug into the surface of the blue ice at the surface to act as a sump, collecting the returning drill fluid where it could be pumped back into the filter tank, as shown in **Figure 45**. The filter tank is a 66-gallon HDPE tank that uses gravity to filter the dirty fluid through 50 or 100 micron filter socks. When drilling is complete, a fluid bailer is used to collect the drill fluid that is left in the hole after the drill rods are removed. The fluid bailer is simply a drill rod with a one-way valve at the bottom; allowing fluid to fill the tube but sealing the gate while the tube is brought to the surface.

Figure 45: Sump pit cut from the solid blue ice at the surface. The drill fluid is pumped through the drill rod and returns to the surface where it is collected in the sump.

When solid ice is not present at the surface but instead the surface is covered by meters of porous firn, the firn borehole must be cased. The Winkie Drill uses thin wall BTW drill rod as casing. The BTW inner diameter is nearly identical to the AW34 borehole diameter, 1.909 inches and 1.895 inches respectively, and is 10% lighter than standard AW casing. The casing is sealed to the borehole with an inflatable packer designed by QSP Packers, LLC. The packer has a 2.0 inch through diameter and 3.5 inch resting diameter. The inflatable element length is 34.5 inches and can be inflated to a maximum diameter of 6.5 inches to a pressure of 700 psi. The element has been wrapped in nitrile rubber for chemical compatibility with the Isopar K drilling fluid. The packer is inflated by air, compressed with a portable air compressor and dried through a desiccant. This packer has not yet been used in the field but is scheduled for deployment with the system during the 2019-2020 Antarctic season. Similar inflatable packers have been successfully implemented in ice with the ASIG Drill.

The ice-enabled Winkie system has successfully completed two Antarctic campaigns, and it is instructive to compare the operations at both. The first campaign to the Ohio Range resulted in the retrieval of six sub-glacial rock cores. Borehole and sample depths can be found in **Table 8**. The five-person crew and all the camp and drill gear was flown to the drill site in six Twin Otter flights. The camp was in place for 25 days, with 15 of those days dedicated to drill operations. All boreholes were through solid ice at the surface, without the presence of firn. One borehole intersected a crevasse, but sufficient drill fluid was available at the site to collect the core with total fluid loss. A total of 160 gallons of Isopar was lost during the season.

Table 8: Ohio Range sample depths and core lengths.

Borehole	Depth [m]	Rock Core Length [cm]
#1	26.53	57
#2	12.08	38
#3	12.90	67
#4	27.00	Gravel
#5	28.33	60
#6	30.00	n/a
#7	25.50	28
#8	54.86	n/a

The second deployment of the system was to the debris-covered Ong Valley, at the site shown in **Figure 46**. A seven-member crew was deployed for 28 days, including 17 days of drill operation. Two boreholes were drilled, each collecting samples from the surface to the final depth. The first borehole reached a depth of 9.45 meters and the second, 12.36 meters. Unlike the bedrock samples collected at Ohio Range that were solid rock, the mixed-media cores from Ong Valley were a mixture of ice and rock particles. The mixture varied from clear ice veins to almost dry sand, as can be seen in **Figure 43** above. Only 20 gallons of Isopar K was lost over the entire season.

Deployment of the ice-enabled Winkie Drill during the 2019-2020 Antarctic season will be at a site that has a significant amount of firn covering the glacial ice. This project will leverage the use of the existing IDP Badger-Eclipse Drill to create the access boreholes through the firn and ice to bedrock. This decision was made in part because using augers would result in a significant amount of chips left in the borehole, and also for weight and ice sampling considerations. The method used to create an access hole through firn and ice to the underlying bedrock depends on site conditions, available logistics, and nature of cores required by the science project.

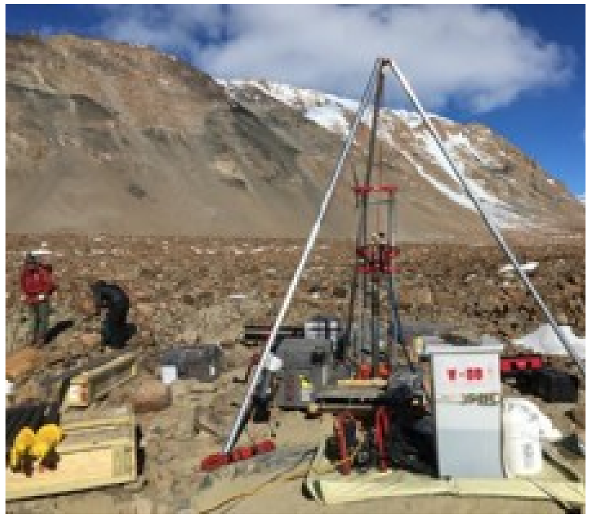

Figure 46: The ice-enabled Winkie Drill as assembled at borehole #1 at Ong Valley.

7.4 Drilling Englacial Access Holes

On topics ranging from glacial dynamics, sedimentary systems, and polar biology, scientists often seek to measure characteristics of the environment within or beneath the ice sheet, and hence they need a hole for access into or through the ice, but not an ice core. Similarly, for seismic studies, holes are needed down to depths of approximately 100 m to serve as shot holes for explosives. Drilling access holes in the ice can often be achieved at a much faster rate than retrieving ice cores, although for deep drilling, the amount of equipment and fuel becomes large in either case. The following sections describe various methods of drilling holes in glacial ice, and the resulting performance of the drills.

7.4.1 Rapid Access Isotope Drill

A novel method of drilling has been developed that creates a borehole but also permits low-resolution isotopic sampling of the chips retrieved from drilling the hole. The Rapid Access Isotope Drill (RAID) is a novel, field-proven technique for rapid ice drilling to a theoretical depth of 600 m that has been developed by the British Antarctic Survey (BAS) [Rix et al, 2019]. It has successfully drilled to 461.58 m in approximately 104 hours at Little Dome C in Antarctica, creating a borehole and also retrieving the chips from the drilling that facilitated 20 cm resolution isotopic sampling of the ice to 25 kyrs.

The RAID was designed to help in the search for suitable sites for a deep ice core through kilometers of ice where ice older than one million years may exist. For this search one of the most important unknowns is the Geothermal Heat Flux (GHF). Ice sheet modelling suggested that only a short temperature profile of the upper 20% of the ice sheet is required to constrain a model that would allow reasonable estimates of GHF. The accuracy of the GHF and the basal temperature estimates is greatly improved when ice samples are also collected to give a paleo-accumulation record, and vertical advection measurements are made using phase sensitive radar (pRES). This modelling and operational requirements in the areas where one million year old ice is likely to be found were used to create the following science requirements for the RAID:

- Produce 600 m borehole as quickly as possible to allow the deployment of temperature sensing system to measure the borehole temperature profile.
- Provide ice samples for stable water isotope analysis.

- Total system to fit in and be light enough (<1000 kg) for a single Twin Otter aircraft to facilitate easy access to remote sites.
- Drill to work in ice at temperatures close to -55°C.
- System to be easily setup and operated by 2 persons.
- Operation to be simple as operators may be working outside at high altitude.

In order to reach the system weight requirement, it was decided that the RAID would be a fast cable-suspended electromechanical ice drill. The drilling time for a cable suspended drill becomes dominated by the winching time as the depth increases. By carrying out full face drilling, no core breaking is required and the winch can be geared solely for tripping up and down the borehole as fast as possible. Ice chips are collected, not an ice core, so core quality is not a consideration, allowing aggressive cutting of the ice. These chips can then be ejected from the drill sonde on the surface by reversing the motor, in the vertical position, minimizing time on surface.

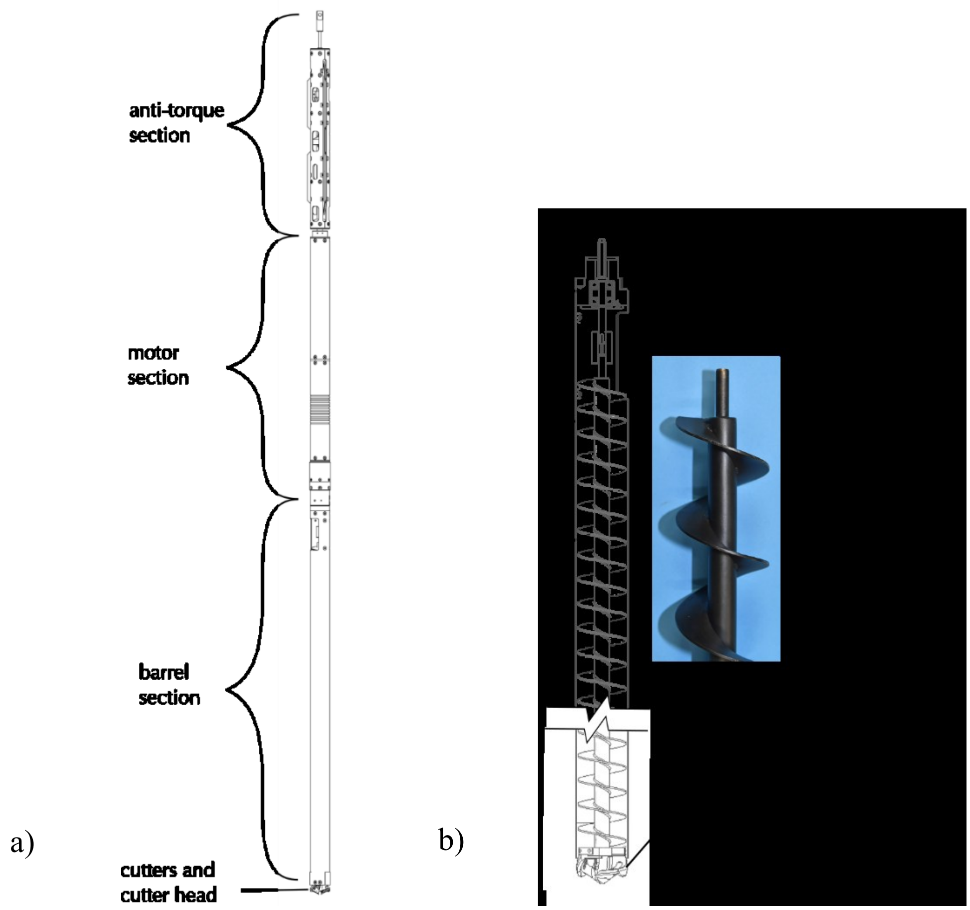

Figure 47: a) RAID drill sonde showing 4 main sections of the drill (with short barrel attached). b) shortened sectional view of barrel showing left-handed inner stationary auger spiral for chip transportation. A photo of the small section of the Xylan coated auger spiral is shown inset.(From Rix et al., 2019.)

The complete drill sonde is shown above in **Figure 47,** which was developed over two test seasons and two field science seasons. A 3-inch (76.2 mm) diameter was chosen for most of the sonde as this allowed for stock off-the-shelf tube to be used for many components. This diameter is a compromise, as a smaller diameter hole requires less power to cut through the ice; space constraints become a problem when smaller than this. The anti-torque section is a reduced size version of the BAS shallow drill which uses both springs and a cam to press six blades against the borehole wall. The motor section houses a 400 W brushless motor with an epicyclic reduction gearbox along with power conversion electronics and a motor controller. An unusual feature in the design is that the outer barrel is attached to the cutters and rotates while a central auger spiral is stationary. An off-the-shelf 10 SWG (3.125mm) thick, barrel was chosen to form the chip collection chamber, at nearly the full allowable length to fit into a Twin Otter aircraft. The barrel section with auger spiral is shown in more detail in **Figure 48a**. Scoops at the bottom of the barrel, visible in **Figure 48b,** push chips onto the spiral and the spiral directs them up the barrel in roughly the order that they were drilled. This design allows the outer barrel to be the higher torque carrying component, rather than the auger spiral, though this necessitates a short barrel to start the drilling process until the anti-torque section is below the surface with the long barrel. Cutters are scaled down lazer-style ice auger cutters more commonly used for opening holes in frozen lakes for fishing.

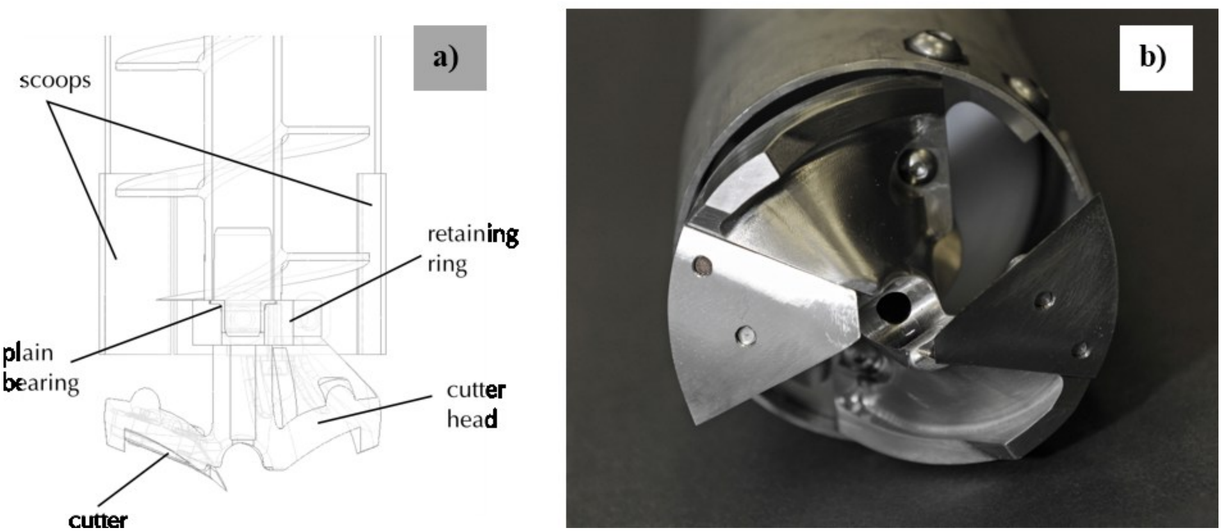

Figure 48: a) schematic of the cutter head and scoops; b) photograph of the cutters with 82.5 mm outer tip to outer tip dimension and cutter head. From Rix et al., 2019.

The drill sonde is suspended from a 650 m, 4.72 mm diameter cable with four 24 AWG (0.2 mm^2) conductors. Two conductors are used to carry the nominal 385 VDC for power. The other two conductors and the armour are used for CAN Bus communications from the surface controller to the motor controller in the drill sonde. The winch uses a 2.2 kW single phase motor with encoders on both the cable drum and the motor. This allows both low speed drilling and high speed tripping to be well controlled. Drill speeds as low as 0.05 m min^{-1} at the bottom end and higher than >80 m min^{-1} when tripping can be achieved, however the winch is only capable of a pull force of 175 kg. The winch controller uses a single axis joystick with a mechanical zero position interlock for manual control but also has controls for automatic deployment, drilling and recovery of the drill sonde. The controller can be interfaced to another controller or computer to allow fully automated drilling but this has not been implemented yet. An RS-232 port also outputs all winch data (cable speed, wire out, deepest depth reached and load) which is logged every second by the drill controller.

The drill controller provides the high voltage supply to the drill sonde and communicates with the motor controller in the motor section of the drill. Drill speed and motor current data is returned digitally from the motor controller and logged by the drill controller. Typical data logged for a couple of drilling runs are plotted and shown in **Figure 49**.

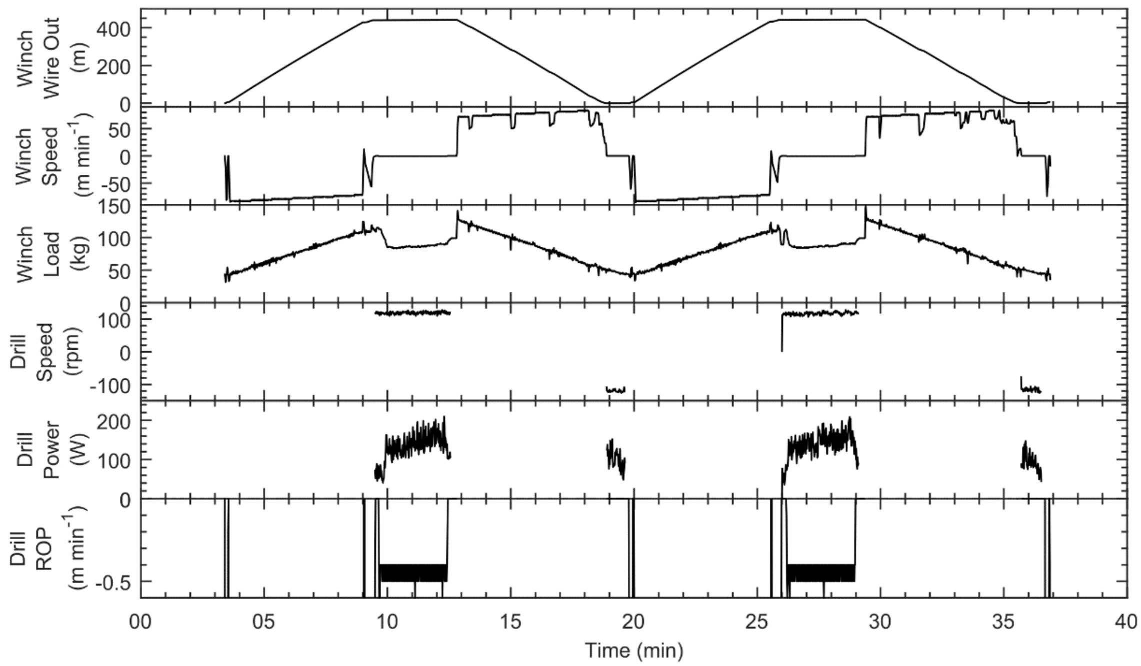

Figure 49: Typical data showing information logged by the drill controller. Drill current has been converted to drill power. This plot shows that winching speeds >80m min^{-1} are achieved and drilling rate of penetration is ~0.45m min^{-1}. Where the drill speed is negative, the chips are being unloaded on the surface which can be achieved in less than a minute. From Rix et al., 2019.

A mast that splits into two parts attaches to the base of the winch. The highest point of the mast when raised is 9.9 m above the snow surface. The system can be ready to drill about 4 hours after arrival on site. Full system weight is approximately 650 kg including tools, generator and spares. A photograph of the Rapid Access Isotope Drill in the field at the Sky Blu site is shown in **Figure 50.**

Having successfully proved the concept of this drill, scientists have suggested new science applications. Drilling to bedrock to obtain a coarse resolution climate record at Sherman Island in Antarctica will be attempted in the 2019-2020 Antarctic season. A percussive rock drilling head has also been designed and built for collecting rock samples once the RAID has drilled to bedrock. The percussive head, P-RAID, attaches to the RAID anti-torque section and reuses much of the RAID system. A rock core of ~20 mm in diameter and up to 30 cm long will be collected for cosmogenic dating. Full automation of the drilling utilizing the remote control capability of the winch controller should allow unattended drilling to occur. A large diameter (230 mm) version of the drill, BigRAID, for deploying instrumentation to a depth of about 200 m is also being designed.

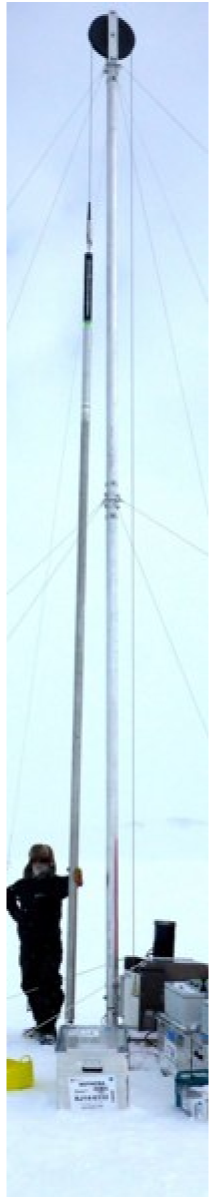

Figure 50: Photo of RAID drill during test season at Sky Blu.

7.4.2 Hot Water Drilling

Access to depths within or beneath a glacier or ice sheet that does not require a core can be rapidly achieved through use of hot water drills. These are often used to access subglacial lakes, or the ocean beneath an ice shelf, or to provide access for sampling subglacial sediments. The use of hot water to melt a hole through the ice does not require a drilling fluid, thus is also amenable to sterilization for clean access in the case of biological sampling within or beneath the ice. The amount of equipment and fuel needed for hot water drilling rises as the hole diameter and depth requirements rise. Description of several recent systems and their operating characteristics are described below.

7.4.2.1 Scalable Hot Water Drilling Systems

Since the advent of hot water drilling in the 1970's, drill systems have generally been designed for specific projects with a narrow range of borehole depth and diameter requirements. The majority of subglacial access boreholes are less than 1000 m, encompassing many grounded ice areas, grounding line regions where the ice sheet goes afloat on the ocean, and all but the thickest parts of the floating ice shelves. Subglacial access holes provide safe passage for oceanographic or glaciological probes, samplers, and permanently deployed instrumentation strings into the underlying ocean or basal sediments.

Recently, new drills have been made scalable by using multiple compatible modules, allowing easy expansion or reduction of the drill system size, to meet borehole and logistics requirements of specific field projects in remote locations. In 2009, the British Antarctic Survey (BAS) started building a new scalable hot water drill, primarily for use on the ice shelves around Antarctica, to enable the study of ice-ocean interactions, ocean properties, ocean circulation, and collection of water samples and sediment cores. The original drill requirements were:

- Provide access holes through ice shelves between approximately 100 – 1000 m thick.
- Operate in ice temperatures down to -30° C.
- Drill and maintain 30 cm diameter access holes.
- Deep 1000 m holes to be drilled in less than 15 hours.
- Be transportable by Twin Otter aircraft and skidoo traverse.
- Be movable and operable by a maximum of 4 people.
- Facilitate safe recovery of probes and samplers from ocean into borehole.
- Maximize fuel efficiency.
- Minimize drill system weight but maximize system reliability.
- Minimize drill setup and tear-down times.

The scaling concept was to optimize the system components to allow additional components to be added as energy needed for drilling requirements increased. The BAS ice-shelf hot-water drill (HWD) is an example of a scalable drill, using a standardized range of modular units to build 500 m and 1000 m versions; the 500 m depth version is shown in **Figure 51**. Initially configured for depths up to 500 m, the drill was first used during the 2011-2012 Antarctic field season to access the ocean cavities and sea floor sediments beneath sites on Larsen C and George VI ice shelves. Over three field seasons, beginning in 2014-2015, the scaled-up 1000 m system provided access holes, up to 891 m deep, at ten locations on Filchner-Ronne Ice Shelf, Antarctica; as seen in **Figure 52.**

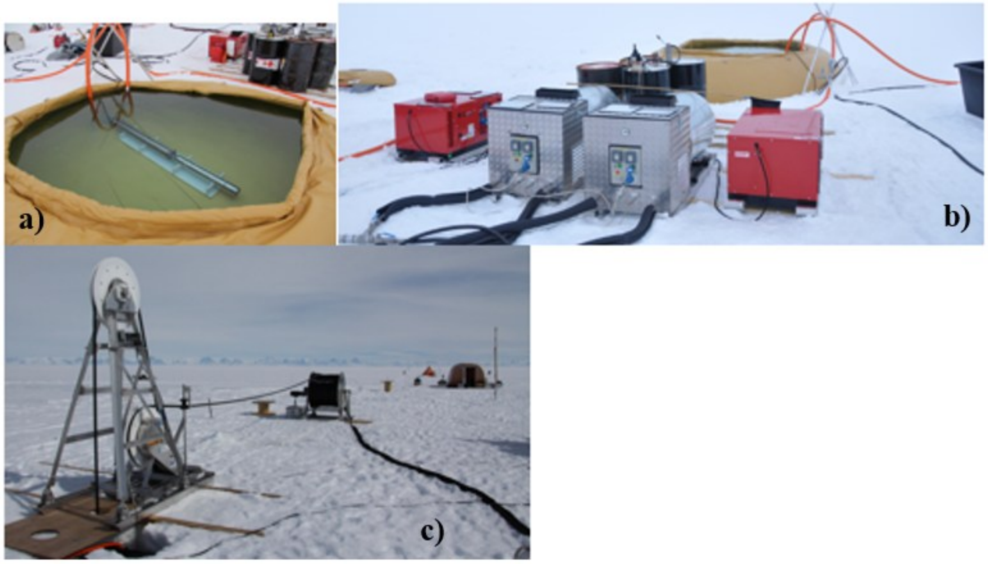

Figure 51: Ice shelf HWD, 500 m configuration. a) Primary drill pump 5.5 kW submersible pump in water tank, b) 250 kW water heaters without heat recovery units and 15 kVA generator (red) with one on standby, and c) the hose winch reel, capstan, and tower with instrumented sheave.

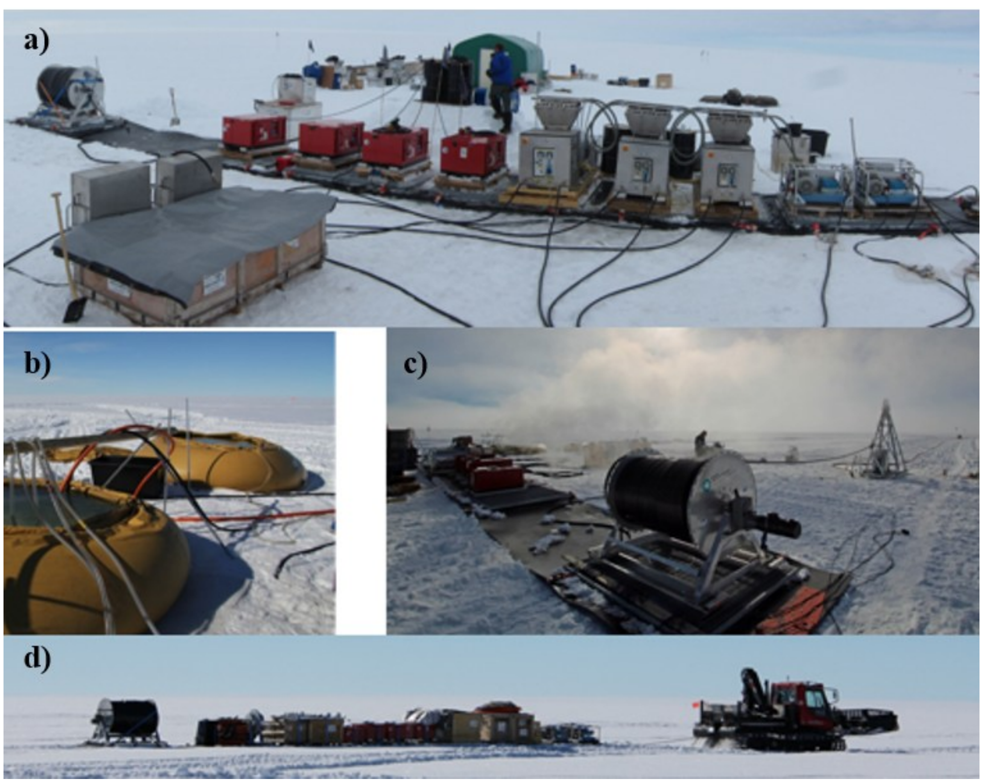

Figure 52: Ice shelf HWD, 1000 m configuration. a) Mounted on a plastic sled (left to right), hose reel, four generators, three water heaters with heat recovery units, four primary surface

pumps with one as standby, b) two water tanks, c) hose winch system and plastic sled with drill units, and d) drill transportation between sites.

Schematics of both systems are shown in **Figure 53**. The scalability allows for redundancy in components, and also can result in logistical savings in shallower borehole cases when a single larger system would be oversized.

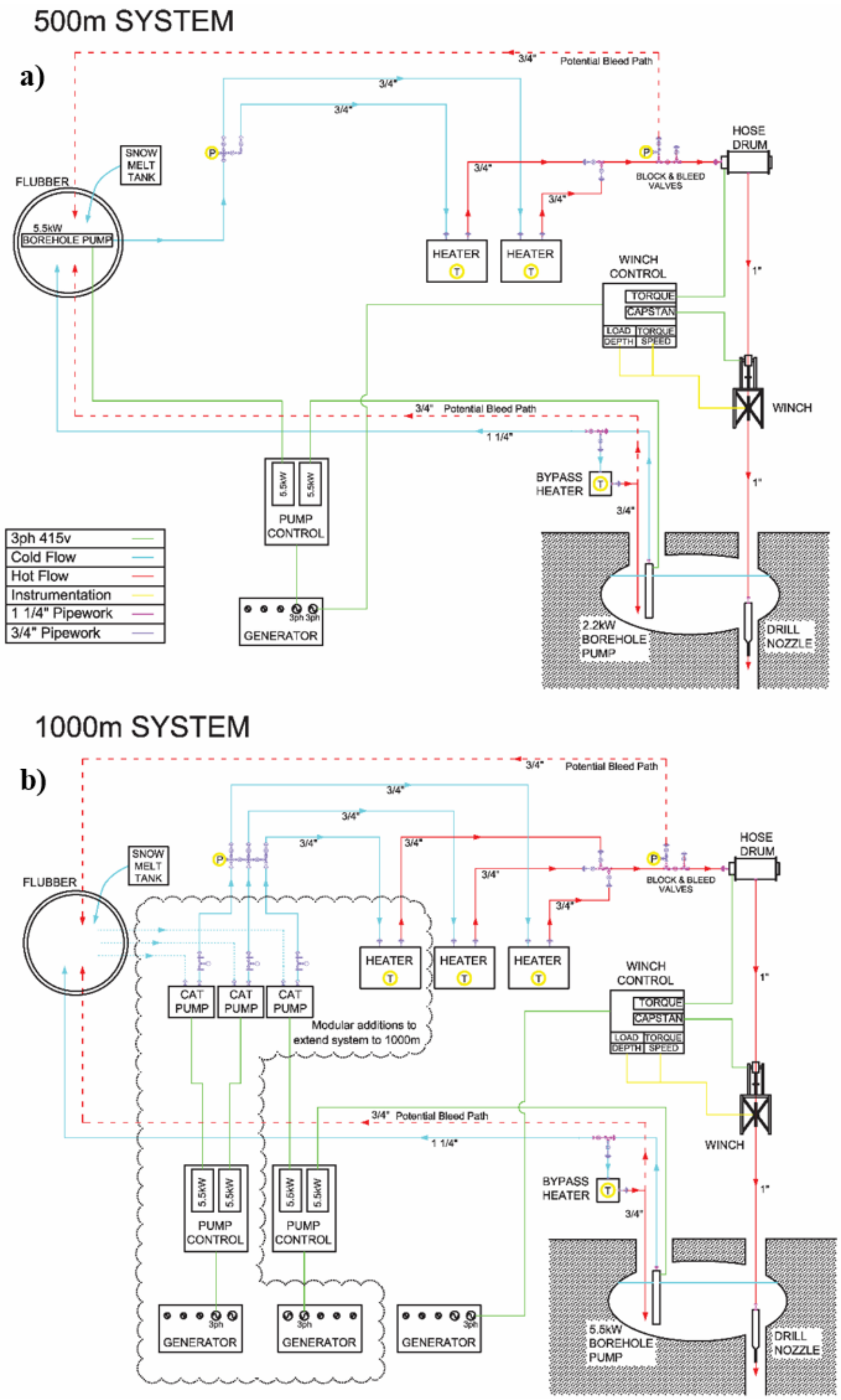

Figure 53: Schematic of the hot-water drill system for (a) up to 500 m ice depth and (b) up to 1000 m ice depth. The additional equipment required for the upgrade to 1000 m is inside the scalloped outline, and the 5.5 kW borehole pump is reused in the cavity. From Makinson and Anker 2014.

7.4.2.1.1 Thermal and Electrical Requirements

The diameter, depth, and time requirements to drill a 1000 m hole, for example, defines the minimum upper thermal requirements. To melt a 1000 m column of ice, 30 cm in diameter at -30°C requires almost 26 GJ to melt, hence a hot water drill with a 750 kW thermal capacity for example, would require almost 10 hours to deliver that energy. In addition, further energy and drilling time is needed to account for heat conduction into the surrounding -30°C ice.

Simple thermal modelling of the drilling process accounting for the thermal losses along the drill hose, the energy delivered to the drill nozzle and the time dependent refreezing of the hole, indicates that the 750 kW thermal input is sufficient for the 1000 m, as shown in **Figure 54**. The heat loss along the thermally leaky drill hose is not wasted; rather it is essential in reducing or preventing refreezing above the drill nozzle, reducing the risk of entrapment when the drill is recovered to the surface.

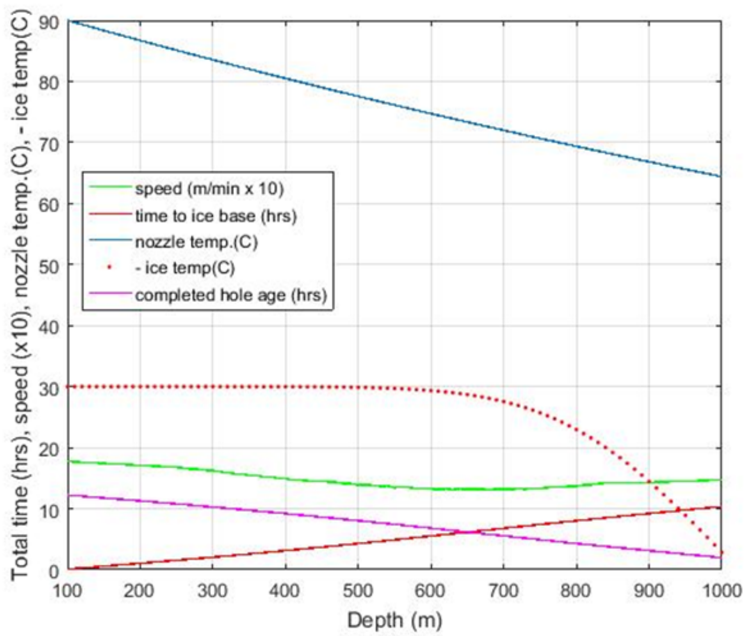

Figure 54: Plot showing the variation of nozzle water temperature (°C), an estimated (negative) ice temperature (°C), x10 for clarity drilling speed (m min^{-1}) , the time taken (hours) and the age of the 30 cm dimeter hole at completion (hours), with depth. Drilling commences from the cavity depth.

HWD electrical power requirements are largely defined by drill water pumping and the recovery of the return water to the surface, which are a function of pressure and flow. With the flow rate defined by the thermal requirements and assuming a maximum operating temperature of 90°C, the drill operating pressure is defined by the hose diameter, as the length is fixed. The operating pressure of the primary pump in the water tank on the surface pressure can be calculated using forms of the Darcy-Weisbach equation

$$Pressure = \frac{f_d L \rho v^2}{2D} = \frac{8 f_d L \rho Q^2}{\pi^2 D^5} \quad (1)$$

where the dimensionless friction coefficient (f_d) is < 0.02 for hoses and 0.03 for heat exchanger coils, L and D are the hose length (m) and internal diameter (m), v and Q are the mean flow velocity (m s^{-1}) and volumetric flow rate (m^3 s^{-1}), and ρ is water density (kg m^{-3}) and pressure is in units of Pa.

The pressure at the submersible pump in the borehole, which is used to recover cold return drill water to the surface of the ice shelf, is the sum of the pressure from the hose friction and the elevation gain from the water level in the borehole to the surface. A schematic of the situation is shown in **Figure 55**. On ice shelves, the water level is determined from the ice shelf thickness (H (m)). The water level depth (h (m)) can be estimated using the following equation:

$$h = H - \frac{\rho_{sw}(0.892H - 17)}{\rho_{hw}} \quad (2)$$

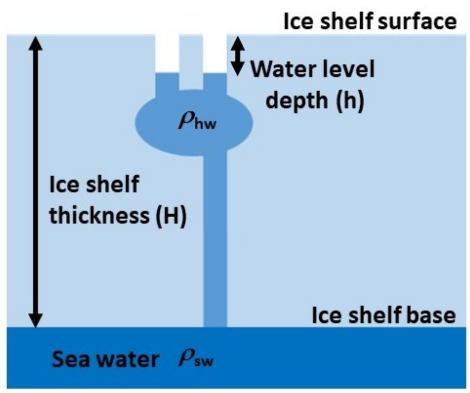

Figure 55: Schematic of borehole water level depth on an ice shelf.

where ρ_{sw} is the seawater density (1027 kg m^{-3}) and ρ_{hw} the hole water mean density which is typically fresh melt water (1000 kg m^{-3}). For ice shelf thicknesses of 100 m to 1000 m, the water level depth ranges from approximately 26 m to 102 m or 28 m to 125 m if dense seawater fills the borehole. On ice shelves where surface melt occurs, surface firn densities will increase, reducing h by several meters, to a maximum of around 17 m when only solid ice is present. Note: 10 m water column exerts a pressure of approximately 100 kPa.

For the drill water pressure, the height between the surface and water level effectively provides additional pressure, though this is usually offset by the pressure across the drill nozzle. With operating temperature, flow rate, thermal power, hose diameter, pressure, and electrical power defined, optimization of scalable drilling equipment modules and procedures to meet the remaining drill requirements can be calculated.

7.4.2.1.2 Drill Equipment

A unique feature of hot water drilling in polar environments is that even brief stoppages can result in rapid freezing of water in surface equipment, hoses, and the drill hole, which can lead to further delays and even loss of the drill, the hole, and damage drilling equipment. Drill equipment and procedures need to be sufficiently robust to accommodate any system failure to ensure consistent drilling operations. All drill equipment should include some level of redundancy and flexibility, and ideally should be repairable in the field. A wide range of spares, common to as many units as possible, should also be available. The components detailed below form the modular and scalable BAS ice-shelf hot-water drill.

7.4.2.1.3 Variable-Frequency Drives (VFD)

With increased reliability, cost effectiveness, power efficiency, and dynamic flexibility, three phase motors with Variable-Frequency Drives (VFD) are fitted to all pumps and winches. Consequently, much smaller, lighter three-phase 50 Hz generators, with petrol engines can be used. Large electric motors were then sized to take approximately all, half, or quarter of the power delivered by each generator for maximum efficiency. Furthermore, as most motors can easily run at 60 Hz, motor speeds can be increased by 20% if required, offering greater drill system flexibility

7.4.2.1.4 Electrical Generator

Three-phase (400 V) and single-phase (230 V) power at 50 Hz is delivered using Europower super-silenced EPS15000TE 12.5 kVA generators. Minimizing weight and volume were key logistic constraints; hence, petrol engines at approximately half the weight of equivalent diesel units were selected. The 500 m system operates on one unit, with one on standby, and the 1000m system uses three, with one on standby.

7.4.2.1.5 Surface Water Storage

The ensure a supply of water for the drilling process, surface storage in the form of robust flexible coated fabric tanks with a 10,000 L capacity are used; see Figures **51** and **52** above. Water held in the tank is usually maintained at 5°C to 15°C to mitigate against freezing in hoses and pumps, therefore insulation under the tank is needed to prevent it from melting into the snow surface. When not in use, these tanks are lightweight and pack down into a small volume.

7.4.2.1.6 Primary Drill Pump on the surface

With relatively low operating pressure, the 500 m system uses a Caprari E6X25-4/24 multi-stage centrifugal submersible pump with a 5.5 kW motor, capable of delivering 90 l min^{-1} at 2100 kPa, and is located in the surface water tank. A key safety feature of centrifugal pumps is that they can never over pressure and damage the drill system. Operating at higher pressure, the 1000 m system uses three positive displacement CAT1531 plunger pumps, each with a 5.5kW motor, and capable of delivering ~40 L min^{-1} at 6900 kPa. These pumps require pulsation dampers and pressure relief valves with backups fitted on each unit.

7.4.2.1.7 Borehole Pump and Umbilical

Cylindrical multi-stage centrifugal submersible pumps are used to return water to the surface via a plaited umbilical consisting of a 32 mm bore thermoplastic return hose, and a 19 mm bore thermoplastic hose to deliver hot water to the umbilical and pump to prevent freezing, and a three-phase power cable. A current loop water level sensor with a shielded cable also runs alongside the umbilical. The 500 m system uses a Caprari E4XP35/20 multi-stage centrifugal submersible pump with a 2.2 kW motor, capable of delivering over 120 l min^{-1} from 70 m depth. The 1000 m system uses a Caprari E6X25-4/24 multistage centrifugal submersible pump from the 500 m system, which is capable of delivering over 140 l min^{-1} from 125 m depth. The return flow to the surface is regulated to balance the flow of water in and out of the subsurface cavity.

7.4.2.1.8 Water Heaters

Commercial high-pressure 250 kW water heating units have been modified for field use and can be transported by Twin Otter aircraft. The units use Kerosene or Jet-A1 fuel and are fitted with adjustable high-temperature and low-flow cut-off switches. Secondary heat exchangers are fitted to the exhausts, and the recovered heat warms the water storage tank. Two heaters are used for the 500 m system, and three for the 1000 m system. A smaller 60 kW water heater maintains the down hole pump and umbilical against freezing.

7.4.2.1.9 Drill Hose Winch System

The winching system is comprised of a powered hose reel, a capstan drive mechanism, an instrumented sheave tower and control panel, all of which can be disassembled and transported by Twin Otter aircraft. The hose reel holds up to 1000 m of drill hose, and a three-phase AC motor in torque mode provides the continuous tensioning in the hose leading to the capstan unit, irrespective of rotation rate or rotation direction. The AC motor is fitted with an encoder to ensure its smooth operation in all modes of operation. In the event of power loss, a motor brake is applied immediately to prevent freewheeling of the reel. During recovery of the drill, the hose is winched to the surface and the hose reel level winding is done manually.

The capstan consists of a grooved wheel with a circumference of 2.5 m and rubber beading at its base to increase friction with the drill hose. The groove is matched to the drill hose diameter and the three quarter wrap around the capstan provides sufficient grip to power the drill hose up and down the hole provided 5-10% back tension is applied by the hose reel unit. The speed range of 0–9 m min^{-1} can be controlled in increments of <0.05 m min^{-1} which is needed during drilling and recovery. The capstan is powered by a three-phase AC motor, fitted with an encoder, via self-locking worm gearbox that prevents overhauling of the motor by the hose tension.

The winch tower has an instrumented sheave wheel, identical to the capstan wheel, which gives a clearance of 3m above the hole for easy deployment of the drill nozzle as well as probes and samplers. The sheave and capstan wheels are both oversized for the hose bend radius, however, if the hose has couplings, the large diameter helps prevent bending damage to the hose at the coupling ends. The tower can be used with or without the capstan for the deployment of coring and sampling equipment, oceanographic instruments and moorings.

7.4.2.1.10 Drilling Hose

To eliminate or minimize hose couplings in the drill hose, 500 m lengths of standard 1PDN25 Kutting thermoplastic hose (26 mm bore) consisting of a polyester elastomer lining, a single polyester braid and a polyurethane outer jacket are used. 500 m is the maximum length that will fit in a Twin Otter aircraft. The hose has a maximum working pressure of 6900 kPa with a 4:1 safety factor for dynamic applications, an operating range of –40°C to 100°C, and weighs 0.52 kg m^{-1} in air. It is slightly negatively buoyant in fresh water countering the 0.02 kg m^{-1} buoyancy of the hot water in the drill hose.

7.4.2.1.11 Drill Monitoring

Sensors and display units output the key parameters of drill water temperature, pressure, and flow, as well as drill hose load, drilling speed, drill depth, and borehole water level, which are logged and displayed graphically. Numerous other sensors associated with individual units can also provide useful diagnostics during drilling operations.

7.4.2.1.12 Antifreeze System

When parts or all of the hot water drill are not in use, water must be removed from the system. A tank of 200-400 litres of coloured propylene glycol, axillary pumps, and an air compressor are used the flush items with antifreeze, which is removed with compressed air. For large drill hose reels, it is necessary to clear the hose by rotating the reel until no further water or antifreeze remains.

7.4.2.1.13 Drill Nozzle

The main body of the drill nozzle assembly is a 50 kg brass pipe, 1.5 m long and 75 mm in diameter. Drilling at a predefined rate ensures the drill hangs freely within the hole, with gravity providing the steering mechanism for a straight and vertical hole. Typically, the pressure drop across the nozzle would be in the range of 500-1000 kPa to give an exit velocity of 30-40 m s^{-1} which is essential for rapid hole formation in advance of the drill nozzle. Operating in low ice temperatures with a single forward pointing water spray, a potential problem exists. In drill hoses where a loss in pumping pressure results in hose elongation, a system failure that also includes loss of winching power can quickly result in a spray tip frozen to the hole bottom and blocked with ice. With no heat flow to the nozzle no melting can take place, resulting in the nozzle, hose and hole being lost. By adding six small forward pointing water jets a short distance behind the main spray tip, this problem is avoided and once flow is re-established, melting out of the tip will occur and full drilling can be re-established. Photographs of the drill nozzle are shown in **Figure 56**.

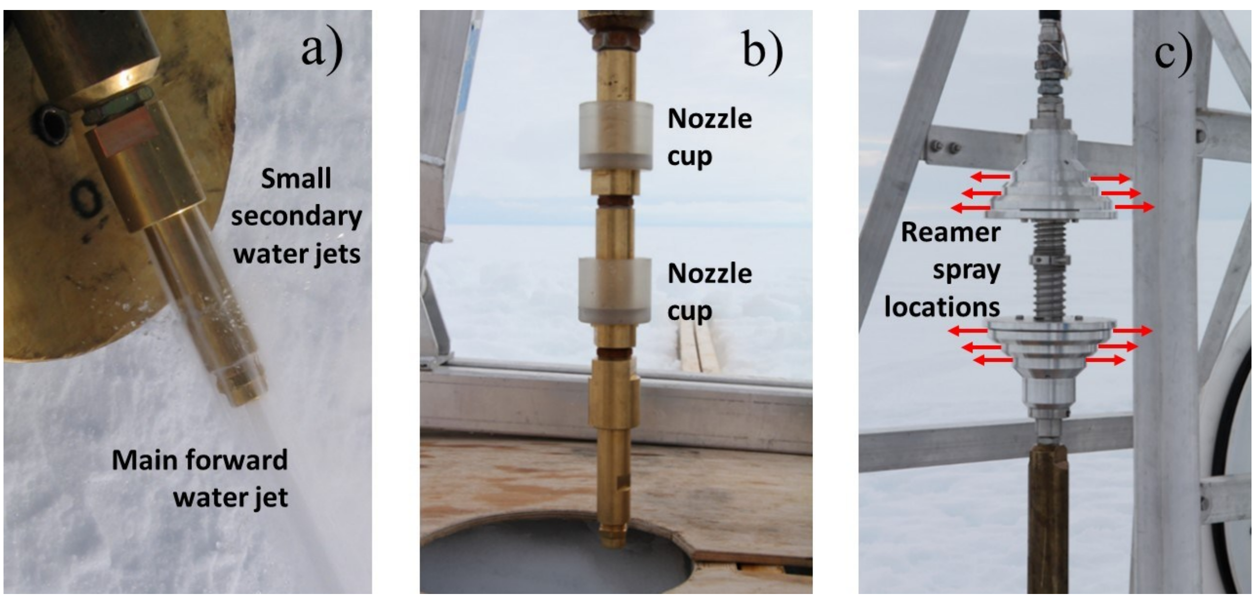

Figure 56: Drill nozzle attachments. a) point jet spray with six small secondary water jets behind, b) nozzle cups for sediment recovery, and c) bidirectional reamer at rear of the drill nozzle.

7.4.2.1.14 Drill Tools

Tools that are used with this hot water drill include sediment cups, reamer, and brush reamer. Each is described below.

7.4.2.1.14.1 Sediment Cups

On ice streams and even ice shelves, substantial amounts of rock debris have been found within the ice, make drilling difficult. To remove or sample such material from drill holes, several collection cups can be added in series to the drill nozzle, so that in the highly turbulent environment of the nozzle tip, sediments are lifted into these simple sediment traps and then recovered with the drill nozzle.

7.4.2.1.14.2 Reamer

The scalable reamer ranges in diameter from 150 mm to 350 mm in steps of 50 mm and is built up from a series of aluminium plates containing holes and channels that are stacked together. It is used to guarantee a minimum hole diameter, particularly before the deployment of larger instruments and is activated when contact is made with a narrowing in the hole when travelling either down or up the hole. When activated, hot water flows through the network of holes and channels and sprays laterally to enlarge the hole.

7.4.2.1.14.3 Brush Reamer

This reamer enlarges the access hole specifically at the ice shelf base only, without needing to enlarge the entire access hole as is the case with the standard reamer. It consists of eight horizontal fan sprays and a flexible brush with 1 mm thick plastic bristles that can traverse a 30 cm borehole and unfold to 1m diameter once beneath the ice shelf base, as seen in **Figure 57**. Pulled up against the ice shelf, the brush separates the hot drill water from the cold underlying seawater, preventing the loss of heat into the ocean and therefore widening the hole at the ice shelf base. By creating a wide bell shaped hole at the ice shelf base, this greatly assists in the recovery of instruments into the hole or the deployment of free-fall probes measuring turbulence at the ice-ocean boundary.

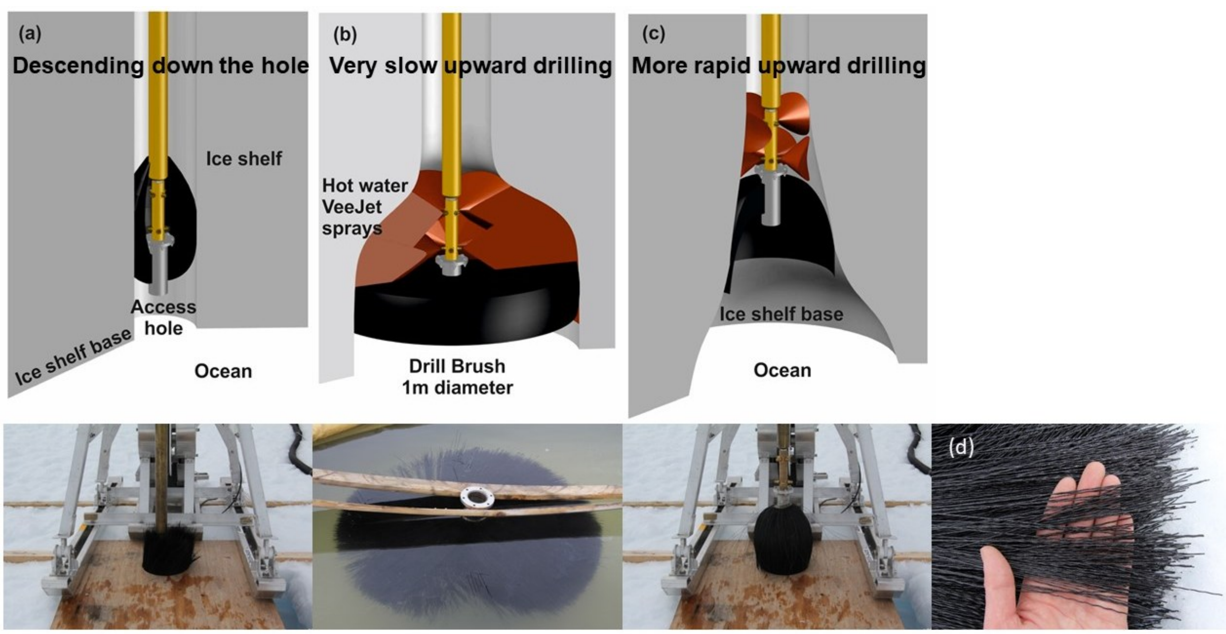

Figure 57: Schematic of the brush reamer at the ice shelf base (from Makinson and Anker 2014) and illustrative surface photographs, a) brush going down the hole, b) brush at base and drilling slowly upward, c) brush near base and drilling quickly upwards, and d) close up of 1 mm dimeter brush bristles.

7.4.2.1.15 Drilling Method

Hot water drills and their drilling process are fundamentally the same using generators, water pumps, water heaters, and a hose with a weighted drill nozzle that delivers a high-speed jet of hot water to melt ice ahead of the drill. Water then flows up the melted hole toward the surface while providing support pressure to the ice walls.

The drilling process initially uses the 10000 L water supply to melt the first hole to a depth below either sea level on an ice shelf or the local hydrological level on grounded ice. The drill is paused to widen the hole and form a cavity before recovery to the surface. A submersible borehole pump is deployed to recover water while a second parallel hole, offset by approximately 0.6 m is drilled and interconnected with the first hole, establishing the water recirculation system cavity. To minimize the period of continuous drilling, the reliance on longer periods of good weather, and the need to operate two drilling shifts, drilling operations cease at this stage. The cavity is pumped dry and the pump recovered. Excess water is stored in a second tank. This temporary stop in drilling and creation of a dry borehole allows water seepage from the porous firn to freeze, therefore avoiding the pump and umbilical potentially becoming frozen to the hole walls.

A day or more later, drilling recommences from the cavity and the borehole pump is redeployed. Once the cavity is refilled, water recirculation is re-established. In the final stages of drilling, a sudden change in water level provides clear confirmation the base of the ice shelf has been reached; after that point the borehole will always contain some water that is susceptible to freezing. Even for a 1000 m access hole, drilling and drill recovery should be complete within 15 hours to avoid shift work. If required, additional reaming at the ice base using a nozzle brush attachment could also be undertaken. Hole availability for deployment probes and samplers is limited to about 12-16 hours as refreezing reduces the hole diameter by at least 5 mm hr^{-1}. If required, periodic reaming maintains the hole diameter before deploying a permanent sub-ice shelf instrument mooring.

Typically, full site turnarounds can be as little as four days for shallow holes and seven days for the deepest holes. New tractor traverse and plastic sled developments now enable transport of the 1000 m drill system almost fully assembled between sites accompanied by a 1350 L insulated bladder holding warm seed water to prime the drill system at the next site. Drill equipment is mounted on several 6’ x 8’ steel pallets, attached to a 72’ x 8’ tractor towed plastic sled. These logistical changes result in highly efficient multi-site hot water drilling operations during a single Antarctic field season.

7.4.2.1.16 Recent Developments

Building on the scalability and modularity of the 1000 m system by adding further generators, a heater, a high pressure pump, and a borehole pump and umbilical, the depth capability has increased to over 2000 m. However, this has only been possible by increasing the drill hose diameter from 26 mm to 32 mm and providing a much larger hose winching system for the single length hose. At different sites on Rutford Ice Stream, West Antarctica, this drill was successfully used in early 2019 when three access holes up to 2152 m deep were drilled to the base of the ice stream.

7.4.2.2 Clean Deep Hot Water Drilling

Subglacial lakes, rivers, and non-oceanic aqueous environments below ice sheets in Antarctica and Greenland are sensitive environments that have been biologically disconnected from the rest of the planet for potentially millions of years. The Antarctic Treaty Code of Conduct requires that exploration of the subglacial aqueous environments be accessed in a "clean" fashion to minimize disturbance and contamination.

The University of Nebraska-Lincoln successfully built and deployed a clean hot water drill system (CHWDS) for deep hot water drilling at Subglacial Lake Whillans; it includes a filtration unit and UV-treatment system to decrease contaminants in the drilling water and provide clean access to the subglacial environment [Priscu et al. 2013]. The filtration technology was successful at reducing microbial bioload in the drilling fluid as per the Antarctic Treaty Code of Conduct. At the Subglacial Lake Whillans site, the CHWDS created an access hole through 800 m of ice; details are further described in [Rack et al, 2014; Blythe et al, 2014]. After repair and upgrade, the drill was recently used again with success for the SALSA project at Subglacial Lake Mercer, Antarctica in 2019. A schematic of the drilling at Subglacial Lake Mercer is shown in **Figure 58**. **Figure 59** is a photo showing the layout of the drilling and science operations at the site.

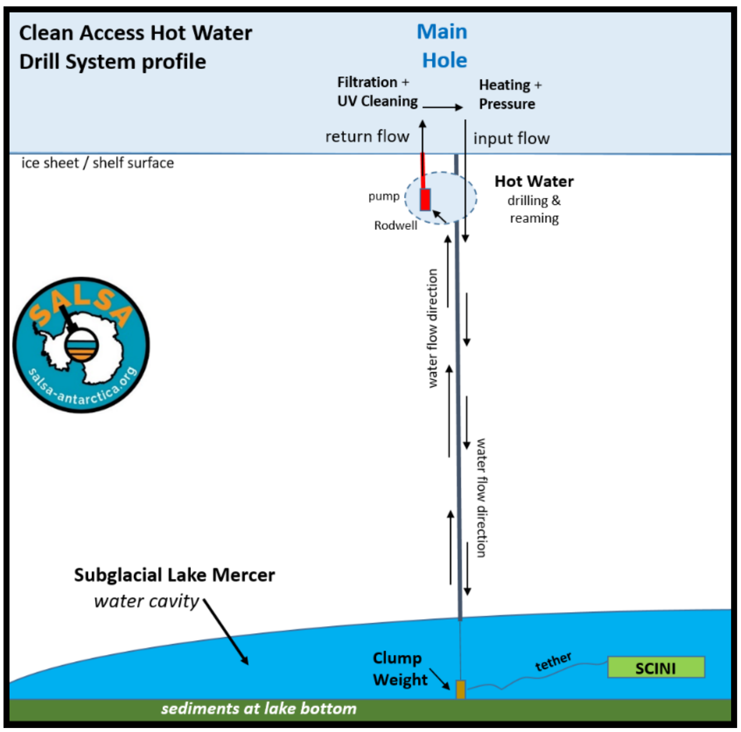

Figure 58: Schematic of the clean access hot water drill system profile at Subglacial Lake Mercer.

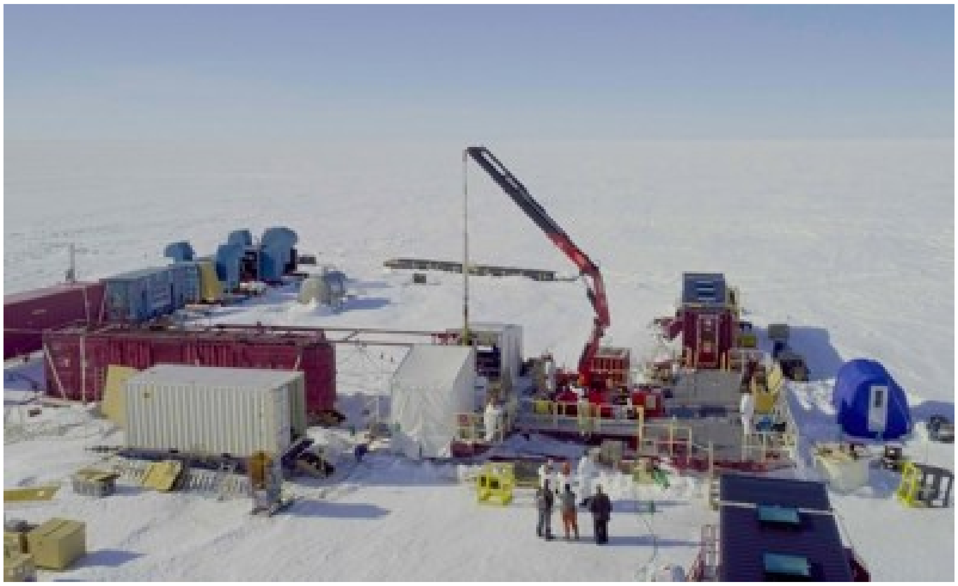

Figure 59: Photograph of the CHWDS operations at Subglacial Lake Mercer in 2018-2019.

7.4.2.3 Shallow Hot Water Drills

Shallow hot water drills are in use by many nations for drilling shallow holes in glacial ice. The IDP Small Hot Water Drill (SmHWD) is a non-coring drill used most often for shot holes for seismic work but has also been used for access holes through a thin ice shelf. The drill is transportable by light aircraft and helicopter.

IDP has two SmHWD systems; in 2015 and 2016, they were modified to improve performance and lessen logistical demands. The heaters were refurbished, the system was upgraded to include modern controls, and a new nozzle kit was created. Lightweight Siglin sleds were purchased to replace the aluminum sled and covers were fabricated for protection from the elements. One of the two IDP systems has a 30-meter depth capability and the second has a depth capability of 60 meters. Each can produce a 2.5 inch diameter hole 25-30 meters deep in about 12 minutes. A photograph of the system in the field is shown in **Figure 60**, and the system specifications are provided in **Table 9**.

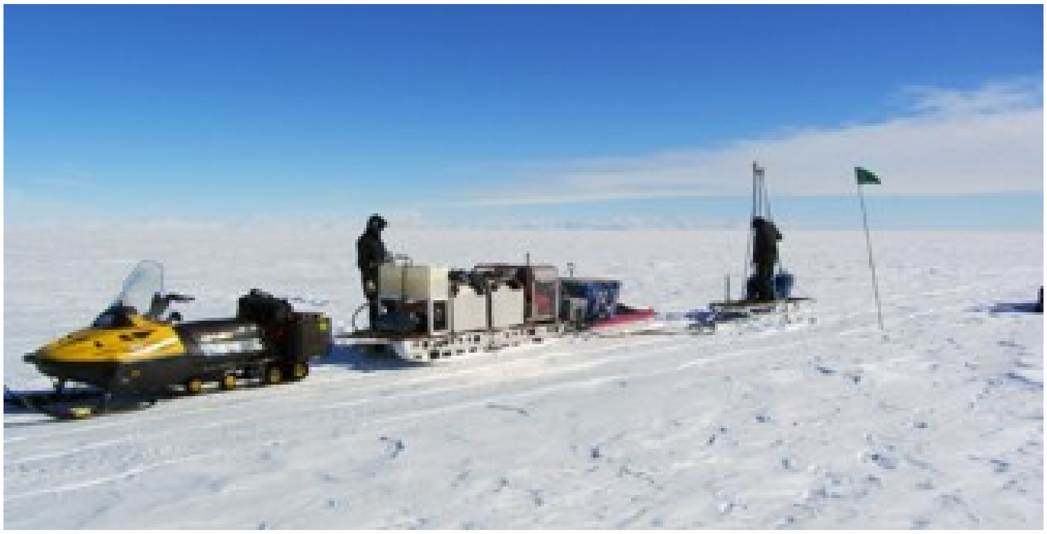

Figure 60: Drilling seismic shot holes with the Small Hot Water Drill on Beardmore Glacier, Antarctica, during the 2012-2013 summer field season. Photo: Maurice Conway [icedrill.org]

Table 9: IDP Small Hot Water Drill System Specifications

Dry Weight	2200 lbs.
Max Piecewise Weight	280 lbs. (heater unit)
Nominal Hole Diameter	Variable (10 cm nominal)
Max Practical Hole Depth	Dependent on conditions; typically reliable and efficient to a depth of 25-30 m; max depth 60m
Fuel Types	Heaters: AN8 Generator/Pump: Gasoline
Crew Size	2
Drill Time	12 min
Cycle Time[1]	30 min

[1] Cycle time for a typical 30m x 10cm diameter hole; includes 15 minutes for set-up and tear-down but does not include time to travel between holes.

The SmHWD is designed to drill quickly through firn. During drilling, no water is recirculated back from the hole. The drill's thermal energy is used both to melt the hole and to melt snow for makeup water through a hot water recirculation loop. The main system components consist of a gasoline-powered pump/generator module and two 60kW fuel-fired water heaters, a water tank and two fuel tanks (AN8 for heaters and gasoline for generator and pump module), as shown in the schematic in **Figure 61**.

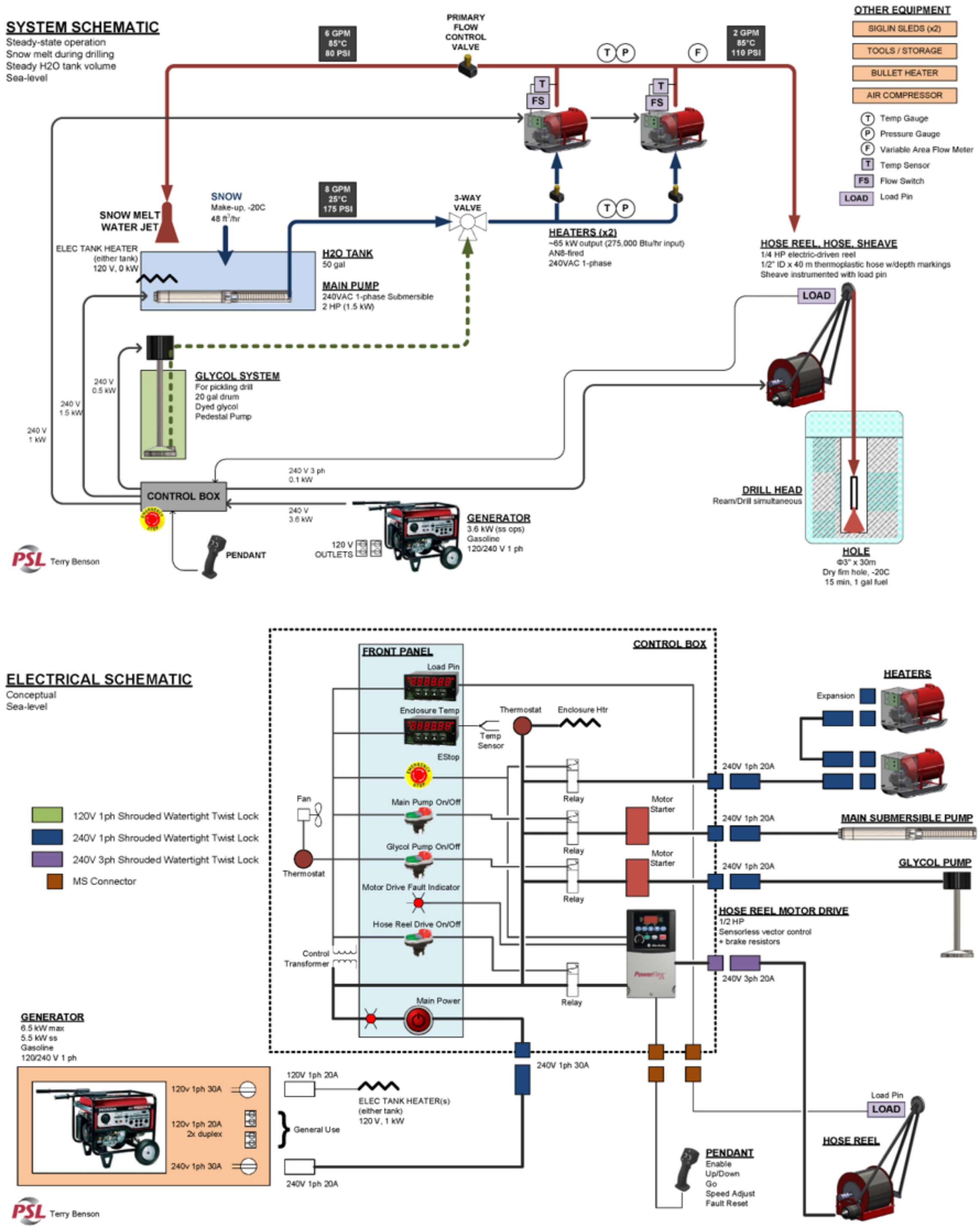

Figure 61: Schematic of the Small Hot Water Drill System.

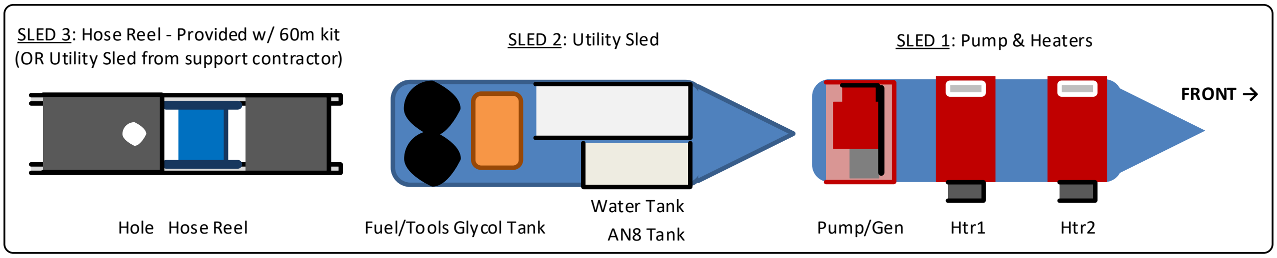

Figure 62: Layout of the IDP Small Hot Water Drill System.

The water is supplied from the water tank and is drawn into the high-pressure pump through a coarse screen filter on the suction line. The high-pressure pump pushes the water through the system and is driven by an 18 HP Honda GX630 gasoline engine. The Honda engine also drives an AC generator. The heaters can be powered from this generator, however, a separate 5 kW electric generator can be substituted for independent power. The engine throttle is adjusted to a 60Hz generator output. At this speed, the pump provides 7 gpm of flow. The maximum discharge pressure of the pump is 1000 psi. A pressure relief valve on the discharge line protects the system from overpressure.

Cold water exits the pump and is directed to the two water heaters through the cold water manifold which is instrumented with pressure and temperature gauges. Flow balancing between the heaters is accomplished by adjusting two brass needle valves, also on the cold manifold.

The customized Whitco Stinger Heaters are diesel-fired, rated to 2000 psi, and instrumented with a temperature gauge. A series of safety interlocks including thermostat-controlled temperature, low flow switch, and over-temperature switch provide reliable operation. Combustion is provided by a standard forced-air burner, comprised of a blower fan, fuel pump, igniter, igniter coil, and burner control module. The output from each heater has its own shutoff ball valve.

Flows from both heaters are recombined in the hot manifold, which is also instrumented with pressure and temperature gauges. Hot water is then split again into the two primary system loops: local recirculation back to the water tank, and flow to the drill head. Local recirculation water is hot water sent back to the water tank to aid in snow melting. The drill head flow is sent through the hose reel and used for creating the borehole. To adjust the flow between the two loops, a flow control needle valve is provided on the recirculation loop. Partially closing this valve will send more flow to the drill nozzle. A vacuum break is also provided on the drill flow circuit at the hot manifold to drain the hose after drilling to prevent freezing.

For the 30 m configuration, a hand-powered hose reel is provided. An electric motor assist is provided for the 60 m hose reel configuration shown in **Figure 62**. The motor is controlled by a foot-switch and a small speed control box. This reel is power by a separate 5kW electric generator.

The drill nozzle stem provides weight so that drilling can be steered straight by gravity, and also integrates the drill nozzle. A nozzle kit is provided with instructions for nozzle selection. When melting snow in the reservoir tank while drilling, a large amount of water is diverted from the drill head for this purpose. With a relatively low flow at the drill head, a nozzle with a small orifice is needed. In this case, about 2 gpm is used for drilling while 5 gpm is used for snow melting. If water reserves are adequate, nearly all the flow can be directed down-hole and a nozzle with a larger orifice is required to keep system pressures from becoming too high.

A simple fuel system supplies the heaters. An elevated marine fuel tank (about 27 gallons) provides slight gravity assistance for the fuel system. The tank is refueled in place using a hurdygurdy pump or other delivery system. Burn rate is about 4 gallons per hour of AN8 fuel. Heaters are set up with a supply hose and a return hose to help avoid having to bleed air from the fuel lines.

With many years of field history and recent refurbishments, the IDP SmHWD systems are expected to continue to be in demand for numerous applications in upcoming Arctic and Antarctic field seasons.

7.5 Conclusion

New technologies spawn new scientific discoveries, and this has been and will continue to be true for scientific drilling in glacial ice. Glaciers, ice sheets, and the subglacial environment contain natural records of past climate, providing insights and clues to understanding future climate. Current climate change is the most pressing environmental issue of our time, affecting every nation on the planet. Scientific discoveries from ice core science have impactful messages, for example the discovery that dramatic changes in climate can occur in less than ten years, and direct evidence from atmospheric gases trapped in polar ice providing the important context that current greenhouse gas levels in the atmosphere are higher now than they have been in over 800,000 years. Rising seas under current climate change threaten major coastal cities around the world; drilling access holes in glacial ice enables scientific discoveries in ice dynamics and subglacial conditions that are important for prediction of future sea level rise.

Innovations in ice drilling in the past decade have yielded both great improvement over earlier drilling techniques, as well as innovative new drilling technologies that foster new avenues of science. Completely inaccessible for cosmogenic dating, bedrock sampling under many meters of glacial ice was impossible before the development of the Agile Sub-Ice Geological Drill; this drill, and its smaller comrade the Ice-Enabled Winkie Drill, are the first of their kind, opening doors to new scientific geological discoveries from previously inaccessible realms. Similarly, scientific demand for evidence of past abrupt climate change from ice cores placed very high demand on ice from certain depths; while drilling additional full ice cores would have been both time- and cost-prohibitive, the new Replicate Coring capability development enables recovery of additional specific bands of ice without the need to drill an entire new core.

Science and engineering go hand-in-hand. Working closely with scientists in the ice-science community, the engineering community continues to rise to meet the need. Major goals in the development of new equipment includes the aim to reduce the footprint of equipment, the amount of fuel required, and where possible adopt renewable energy technologies and environmentally-friendly processes in order to minimize environmental impacts of drilling operations. As we look to the future, further innovations in ice drilling technologies will continue to foster new scientific discoveries of importance to all people.

7.6 Acknowledgements

The authors express our sincere thanks to Editors Yoseph Bar-Cohen and Kris Zacny for inviting us to write this chapter, and for their patience while we worked through the task. Contributions by Keith Makinson and Julius Rix were supported by the British Antarctic Society. The U.S. Ice Drilling Program is a National Science Foundation Cooperative Agreement with Dartmouth including subawards to the University of Wisconsin and the University of New Hampshire; efforts of the U.S. Ice Drilling Program were made possible through funding from the U.S. National Science Foundation through NSF Cooperative Agreements 1327315 and 1836328.

7.7 References

Bentley, C.R., B.R. Koci, L. J-J. Augustin, R.J. Bolsey, J.A.Green, J.D. Kyne, D.A. Lebar, W.P.Mason, A.J. Shturmakov, H.F. Engelhardt, W.D. Harrison, M.H. Hecht, V. Zagorodnov (2006). "Ice Drilling and Coring", *Chapter 4 in Drilling in Extreme Environments*, Y. Bar-Cohen and K. Zacny, eds., Wiley-VCH Verlag GmbH & Co, KGaA, Weinheim. ISBN: 78-3-527-40852-8.

Gibson, C.J., J.A. Johnson, A.J. Shturmakov, N.B. Mortensen, J.J. Goetz (2014) "Replicate ice coring system architecture: mechanical design," Annals of Glaciology 55(68), p. 165-172.

Gibson, C.J., Kuhl, T.W., Johnson J.A., Boeckmann, G.V., Goetz, J.J., (2015) Presentation from the May 28, 2015 Design Review of the Agile Sub-Ice Geological Drill System; Icedrill.org

Johnsen, S., SB. Hansen, S.G. Sheldon, D. Dahl-Jensen, J. P. Steffensen, L. Augustin, P. Journe, O. Alemany, H. Rufli, J. Schwander, N. Azuma, H. Motoyama, T. Popp, P. Talalay, T. Thorsteinsson, F. Wilhelms, V. Zagorodnov (2007) "The Hans Tausen drill: design, performance, further developments, and some lessons learned," Annals of Glaciology 47, p. 89-98.

Johnson J.A. et al. 2014. Next generation of an intermediate depth drill, Annals of Glaciology, Volume 55, Issue 68, 27-33.

Johnson J.A., Mortensen N.B., Gibson C.J., Goetz J.J. and Shturmakov A.J., 2014 DISC Drill and Replicate Ice Coring System Testing, Annals of Glaciology, Volume 55, Issue 68,

Johnson, J.A., N.B. Mortensen, C.J. Goetz, A.J. Shturmakov (2014) "Replicate ice coring system testing", Annals of Glaciology 55(68), p 331-338.

Kuhl, T., et al. 2014 A new large-diameter ice-core drill: the Blue Ice Drill. Annals of Glaciology, Volume, Issue 68, 1-6.

Langway, C.C. (2008) "The Early Polar Ice Cores", Cold Regions Science and Technology 52, p. 101-117.

Mortensen, N.B., J.J. Goetz, C.J. Gibson, J.A. Johnson, A.J. Shturmakov (2014) "Replicate ice coring system architecture: electrical, electronic and software design", Annals of Glaciology 55(68), p. 156-164.

Mulvaney, R., O. Alemany, P. Possenti (2007) "The Berkner Island (Antarctica) ice-core drilling project", Annals of Glaciology 47, p. 115-124.

Rand J and Mellor M (1985) Ice-coring augers for shallow depth sampling. CRREL Rep. 85-21.

Rix, J., R. Mulvaney, J. Hong, D. Ashurst (2019) "Development of the British Antarctic Survey Rapid Access Isotope Drill", Journal of Glaciology, doi: 10.1017/jog.2019.9.

Slawny K.R., Johnson J.A., Mortensen N.B., Gibson C.J., Goetz J.J., Shturmakov A.J., Lebar D.A. and Wendricks T.W., 2014 Production Drilling at WAIS Divide, Annals of Glaciology, Volume 55, Issue 68

Shturmakov, A.J., D.A. Lebar, C.R. Bentley (2014) "DISC drill and replicate coring system: a new era in deep ice drilling engineering," Annals of Glaciology 55(68), p. 189-198.

Talalay, P.S., (2016) *Mechanical Ice Drilling Technology*, Geological Publishing House, No. 31 Xueyuanlu, Haidian District, Beijing 100083, P.R. China. ISBN 978-981-10-0559-6.

Wumkes, M.A. (1994) "Development of the U.S. Deep Coring Drill", Mem. Natl Inst. Polar Res, Spec. Issue, 49, p. 41-51.

Zagorodnov, V.S. (2019) Personal communication.

Zagorodnov V.S. (1988) "Antifreeze-Thermodrilling of Cores in Arctic Sheet Glaciers," Ice core Drilling. Proceedings of the Third International Workshop on Ice Drilling Technology (eds C. Rado and D. Beaudoing), Pages 97-109.

Zagorodnov V, Thompson LG, Ginot P, Mikhalenko V (2005) "Intermediate-depth ice coring of high-altitude and polar glaciers with a lightweight drilling system," *Journal of Glaciology*, Volume 51, Number 174, Pages 491-501, doi: 10.3189/172756505781829269

Zagorodnov, V. and L. Thompson (2014) "Thermal electric ice-core drills: history and new design options for intermediate-depth drilling", Annals of Glaciology 55(68), p. 322-330.

Zagorodnov, V., L.G. Thompson, P. Ginot, V. Mikhalenko (2005) "Intermediate-depth ice coring of high-altitude and polar glaciers with a lightweight drilling system". Journal of Glaciology 51(174), p. 491-501.