Ice Drilling Design and Operations

Long Range Drilling Technology Plan

Prepared by Ice Drilling Design and Operations group in collaboration with the Ice Drilling Program Office

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Cover photo: The Blue Ice Drill at Taylor Glacier. *Tanner Kuhl (IDDO, 2010)*

INTRODUCTION

The IDPO Long Range Science Plan lays out recommended directions for U.S. ice coring and drilling science. This companion Long Range Drilling Technology Plan provides an overview of the multifaceted system of drills and technology needed to advance the science. The report begins with a discussion of the drills and technologies needed to successfully implement the Science Plan. It then discusses field projects that would use the drills. Finally the Technology Plan addresses briefly the funding allocated for its implementation.

ICE DRILLING SYSTEMS AND TECHNOLOGIES

High priority investments identified by the Ice Drilling Program Office Science Advisory Board (SAB; see Ice Drilling Program Office Long Range Science Plan) as needed to enable scientific discovery include:

- Maintaining agile coring/drilling capability
- Two logging winches – one 1 km and the other 4 km with the 1 km the higher priority
- Replicate coring capability
- Procurement of an agile intermediate depth drill
- Conceptual design for access into the ice sheet with a fast, narrow hole
- Conceptual design for upgrades to the DISC drill to enable its use in East Antarctica
- Methods and protocols for clean access for sampling of subglacial environments
- Identify new drilling fluid

To this list IDDO believes should be added:

- A modular hot water drill to allow access to base of ice sheets and subglacial lakes

Note: Items are <u>not</u> listed in priority order.

IDDO will address these priorities either by the maintenance and modification of equipment already in its inventory or by developing or procuring new equipment. The equipment involved in meeting these priorities is addressed in the following sections.

Important technical aspects of the equipment are its performance characteristics – including things such as its transportability, its condition, and the availability of documentation such as component specifications, fabrication drawings, operating instructions, maintenance manuals, etc. In the continuing development of existing equipment IDDO will undertake, to the extent permitted by availability of resources and funding, a systematic program of defining the baseline performance of each of the drills with the compilation of data from field projects and the improvement of equipment documentation. These programs will not only allow IDDO to better maintain the equipment, but will also allow it to undertake modifications that improve the equipment's performance and, hence, it usefulness to the scientific investigators.

Before the end of calendar 2011, IDDO will develop a documentation matrix showing the status of documentation for all its drilling systems.

Agile Drills

Agile coring and drilling capability was seen by the IDPO Science Advisory Board as one of the seven high priority investments in drilling technology needed in the next five years. These drills, which include hand augers, are the smaller systems that can drill holes to depths of approximately 350-400 meters; most are drills capable of recovering core. They are relatively light weight and generally do not require a drilling fluid. IDDO has a number of such systems in inventory and has one hand auger in the development stage.

Chipmunk Drill – The smallest drill in the IDDO inventory, it is a hand-held, motor driven coring drill that collects 2-inch diameter cores in solid ice. It has two barrels, one 15 cm long and one 50 cm long. The drill has been used on one project (for which it was designed) at Pakitsoq, West Greenland, in 2003 and 2004, and for several demonstrations of ice coring for the public in the U.S.

Current Status:	Drill is workable, but improvements are needed: -- Fix wobble due to the looseness of the bayonet mount -- Strengthen springs that hold the barrel in place on the mount -- One of the three bayonet pins tends to pop out
Technical Issues:	Performance Data – None; need process to get user feedback (core quality, etc.) or future IDDO testing to characterize performance Documentation – Exists, but will be reviewed for currency when needed Other – None known
Plans:	There have been no requests for field use of the drill since the original project -- improvements to the drill will be made when required for a field project

Hand Augers – The next larger type of drill is the hand auger. The hand auger is the most basic of the mechanical drills and is driven from the surface by a series of extensions that are added as drilling proceeds into the ice. The drill, like all other coring drills, has to be retrieved each time a core section is recovered. IDDO hand augers come in two different diameters: 3-inch and 4-inch. The 3-inch model takes cores 1 m long; the 4-inch auger can be configured to take either one-meter or half-meter cores. The maximum depth to which hand augers without power assistance (see section on Sidewinder) can be used is approximately 20 meters.

Hand augers are typically operated by the investigator without assistance from IDDO drillers.

Current Status:	Hand augers to be sent to the field are inspected and repaired as needed; in the past a general inventory of augers has been provided to RPSC for issue through the Berg Field Center. Hand augers will still be distributed by the Berg Field Center, but they, like all other agile drills, will now be packed, labeled and issued by IDDO for use by individual investigators. PICO hand augers have been modified to use cutter inserts and cutter holders similar to SIPRE. Drawings, operating instructions, and maintenance procedures have been written. PICO and SIPRE hand augers are aging and IDDO is in the process of developing a replacement. Several sizes of coring hand augers are available commercially.
Technical Issues:	Performance Data – None; need process for quantitative as well as qualitative feedback from users or future IDDO testing to characterize performance Documentation – Most drawings have been completed; operating manuals and a maintenance procedure have been written and are updated annually. Other – Some quality problems, e.g. alignment of mounting holes, parts not fitting properly.
Plans:	1. Correct quality problems of existing hand augers "one hand auger at a time" as they are prepared for issue – Ongoing as necessary 2. The conceptual design for a new, improved hand auger has been completed, detailed design work has begun, with the expectation of testing a prototype in Antarctica in 2011-12.

Plans (continued)	3. Fabricate and deploy for use the new version of the hand auger/phase out PICO and SIPRE hand augers. Investigate reasons some users prefer SIPRE augers so positive features are not lost – FFY 2012 and FFY 2013. 4. Fully implement process whereby hand augers are directly packed and labeled for use by specific investigators rather than providing a general inventory of hand augers to the BFC for distribution. This will allow for the normal IDPO-IDDO procedure for feedback from users, 5. Improve hand augers based on feedback from users – Ongoing 6. Investigate very lightweight "backpack drills" for alpine shallow coring. 7. Investigate clean technologies for such lightweight drills for shallow coring to study microbes in the ice. 8. Develop a questionnaire to get information on hand auger performance.

Prairie Dog – A modification of the hand auger, the Prairie Dog includes a stationary outer barrel that allows operations in solid ice as well as firn. Limit of depth of use is approximately 40 meters (with a Sidewinder). The drill has been used almost exclusively by Jay Kyne, its designer, who is now a contract driller with IDDO.

Current Status:	Drill was lost during the 2010-2011 Antarctic field season -- stuck in the ice at Lake Vida and abandoned rather than risk environmental damage to the site, which is in the Dry Valleys Specially Protected Area.

Technical Issues:	Performance Data – Few exist because of infrequency of use. Documentation – Several system drawings exist in the document control database (11 drawings in all), as well as an operator's manual. Other – None known; more experience with drill needed
Plans:	1. Replace lost Prairie Dog drill 2. Prior to replacing the lost drill: review design of drill, including potential hazards, and determine modifications needed – FFY 2012 3. Modify and construct one or more drills (determined by project need) - FFY 2012 4. Review other documentation available and determine needs; update and create documentation as needed and enter into database – FFY 2012 5. General maintenance and modification - Ongoing as needed

Sidewinder – The Sidewinder is not a drill but a drive/lifting system used in conjunction with hand augers. It is driven by an electric motor (power hand drill) and a winching system to help retrieve the drill string. The Sidewinder extends the maximum practical depth of coring with a hand auger to about 40 m.

The Sidewinders are increasingly being used by investigators without the assistance of IDDO drillers and the trend is expected to continue.

Current Status:	Three working systems are available.
Technical Issues:	Performance Data – Information regarding performance should be systematically collected from users. Documentation – Drawings exist, but need to be reviewed and entered into document control database. Operating procedures for the Sidewinder have been developed and are reviewed annually.

Technical Issues (continued)	It has been suggested that an operator DVD be developed and a hardcopy of the system layout and necessary instructions included with this system. Other – Several potential safety hazards (ladder use, loosening chuck) have been noted in the operation of the Sidewinder; modifications have been made to correct the problems; their effectiveness, however, has not been evaluated.
Plans:	1. Evaluate design and operation of modified Sidewinder, including review of safety concerns, and design required further modifications – FFY 2012 2. Modify Sidewinder systems per design evaluation – FFY 2012 3. Review documentation, update and enter into database – FFY 2012 4. Modifications – As recommended by users 5. Repairs – Ongoing

Blue Ice Drill –An agile drill capable of retrieving cores of approximately 9 1/2 inch diameter to depths up to 20 meters in solid ice. The drill, developed for the University of California at San Diego, was used with great success to collect samples of "blue ice" on Taylor Glacier during the 2010-11 Antarctic field season.

Current Status:	The Blue Ice Drill is undergoing some modifications as a result of the past field season and is scheduled to be ready for use again on Taylor Glacier in the 2011-12 Antarctic field season.
Technical Issues:	Performance Data – A comprehensive account of the drill's performance is contained in the drillers' End-of-Season report. IDDO plans on having one driller/engineer in the field when the drill is used during the 2011-12 field season; one of his responsibilities will be to document the drill's performance. Documentation – Documentation for the drill has been completed and entered in the SSEC document control database.
Plans:	1. Repair and make modifications after 2010-11 and 2011-12 field seasons as necessary – FFY 2011 and FFY 2012

2-Inch Drill – The drill is a highly portable electromechanical coring drill that can be powered by batteries, solar cells, or a generator; cable is wound up and paid out using a hand-powered winch. It was developed and manufactured by Glacier Data in Fairbanks, AK, for rapid, near-surface core collection on the U.S. ITASE project. The maximum depth to which the drill in IDDO's inventory has cored is 42 meters.

Current Status:	Needs repairs and possible modification before being released for use.
Technical Issues:	Performance Data – None, because of lack of use. Documentation – Some from manufacturer; if drill is to be used, documentation should be more fully developed. Other – Engineers/drillers believe that the drill requires extensive modification to be a truly useful tool.
Plans:	1. There have been no requests for the drill since its use on the US-ITASE project and there are no plans to make modifications unless there is a project on which it would be used. It would take considerable time and effort to make the drill usable.

Badger-Eclipse Drills – The Badger-Eclipse Drills are modified Eclipse Drills manufactured by Icefield Instruments, Inc. The drill is electromechanical and takes an 81 mm core to depths of approximately 400 meters. The drill system is transportable by small aircraft or helicopter. There has been an increased demand for use of the drills on field projects and a third Eclipse Drill has been transferred from the University of New Hampshire to IDDO.

Current Status:	The two Badger-Eclipse drills, which have been modified to varying degrees, are available for use. The third Eclipse drill, which arrived from UNH in June, 2010, has not yet been put in condition for issue.
Technical Issues:	Performance Data – Data from several projects have been collected; these data need to be analyzed both to determine their usefulness and to develop some preliminary performance specifications. Procedures for more consistent recording of data during projects need to be defined by IDDO and used. Documentation – Since the basic drills were purchased, IDDO lacks much engineering documentation for the drill although in making modifications to the drill, some "reverse engineering" has been completed and a few drawings produced; 40 drawings are currently contained in the database. Operating and maintenance manuals need to be completed. Other – Improvements to instrumentation and the control system need to be made to improve operational flexibility and reliability. Components of the drills as modified are not entirely interchangeable; however, some variation between the drills may be desirable to accommodate user preferences.
Plans:	1. Repairs and general maintenance to make the drills usable for the 2011-12 Antarctic field season – FFY 2011. 2. Develop procedure, including bill-of-material checklist, for preparing drill for issue – FFY 2011 & FFY 2012 3. Analyze project performance data, develop (if possible) preliminary performance baseline, institute guides for data collection. Continue to collect, analyze data and update performance – FFY 2011 and thereafter 4. Standardize components of the drills to the extent desirable and practicable * – FFY 2011 and ongoing 5. General maintenance and repairs - Ongoing 6. Complete documentation and enter into database – Ongoing with goal of having complete, up-to-date versions in database by the end of FFY 2011 7. Determine desired evolution of Badger-Eclipse drills in general * Participants at the 2010 Drillers' Workshop suggested making downhole equipment interchangeable and surface equipment distinct, with distinct names and transportability options

4-Inch Drill – This is an electromechanical ice coring drill that takes a 104 mm core. Cores can be retrieved from depths down to approximately 400 meters. Winches with 100, 200, and 400 meter cables are available. The drill is of a mature design and has been used successfully for many years. It is particularly useful on projects requiring a larger diameter core than produced by the Badger-Eclipse drills. The drill can be transported by light aircraft or helicopter.

The 4-Inch drills were not used during the 2010-11 Antarctic field season; two were used in Greenland in 2011. General maintenance and minor modifications were implemented on the drills during FFY 2011 Budget requests for FFY2011 and beyond will include upgrade costs.

Current Status:	IDDO plans to have two 4-Inch Drills available for use on field projects, with a third kept in reserve for possible refurbishment. Two drills are currently available for field use, but will require the replacement of some components in the near future. Winch and cable inventory includes two each at 400 m and 200 m and one at 100 m for the electrothermal drill.
Technical Issues:	Performance Data – Data from several projects have been collected; these data need to be analyzed both to determine their usefulness and to develop some preliminary performance specifications. Procedures for more consistent recording of data during projects need to be defined and used. Documentation – The 4-Inch Drills were designed and built by PICO and AutoCad drawings exist, but are not up-to-date. Drawings for more recent modifications have been made; approximately 15 drawings exist in the database. Up-to-date drawings will be completed in 2012. Operating and maintenance manuals need to be completed. Other – The drills are aging and some replacement parts are becoming harder to find. The cable winch sleds are very heavy, making the drill not optimal for transport by small aircraft, but participants in the Drillers' Workshop doubted that huge weight savings could be gained by modifying winch sleds.

Plans:	1. Replace barrels and a very few other components as necessary – FFY 2011 and periodically thereafter 2. Review winch needs – the desired number of each size are in inventory, but all need upgrades and refurbishment. 3. Analyze drill performance data and establish a performance baseline if possible; define data collection procedure – FFY 2012 and thereafter 4. Study feasibility of making lighter winch sleds that would be more easily transported by light aircraft - FFY 2012 5. Complete development of operating and maintenance procedures and documentation – FFY 2012 6. Update drill system drawings and enter into database – FFY 2011 – FFY 2012 (models have been done on this) 7. Perform general maintenance and repairs – Ongoing and as necessary 8. Study feasibility/need of modifying drills for submersible drilling – FFY 2011 & FFY 2012 9. Modify drill(s) for submersible drilling if feasible/necessary and test – FFY 2012 – FFY 2013 10. Determine desired evolution of 4-inch drills in general: sonde similar to IDD? Replace motors, gearboxes etc.? FFY 2012

Electrothermal Drill – This drill melts an annulus around the core. It supplements the 4-Inch drills and can be substituted for the 4-Inch sonde, using the same winching system, for use in ice warmer than about minus 10º C. It takes a 3-inch core. It is particularly useful in ice close to the pressure melting point, where electromechanical drills suffer risk from melting and refreezing of the ice. Much simpler than the electromechanical drills, the electrothermal drill has performed well recently in British Columbia and Alaska.

Current Status:	IDDO has one electrothermal drill. It was repaired, including a new barrel, in 2011: IDDO hoped to test the drill on a project during the summer of 2011 in Greenland, but was unable to do so.
Technical Issues:	Performance Data – Some data from two projects have been collected; these data need to be analyzed both to determine the drill's usefulness and to develop some preliminary performance

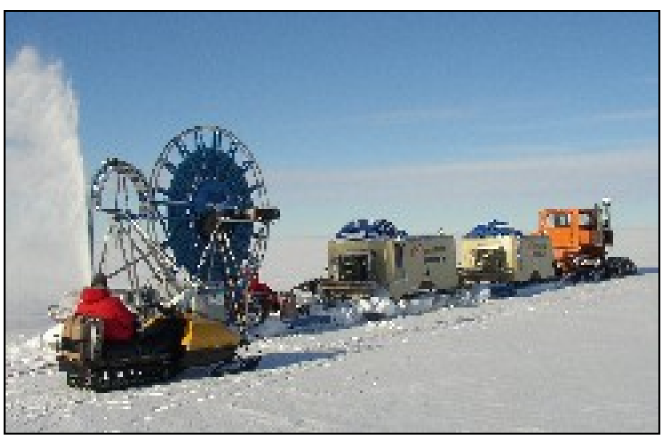
Technical Issues (continued)	specifications. Procedures for more consistent recording of data during projects need to be defined and used. Documentation – Drawings and models for the new barrel are done, but otherwise no drawings or procedures are currently in the document control database. The electrothermal drill was designed and built by PICO and AutoCad drawings probably exist but are out-of-date; they need to be updated and entered into the database. Operating and maintenance manuals need to be completed and entered into the database. Other – The availability of replacement parts is unknown. Inasmuch as the cable winch sleds are the 4-Inch Drill sleds, they are very heavy, making the drill not optimal for transport by small aircraft (see 4-Inch Drill above).
Plans:	1. Develop procedure for preparing drills for issue – FFY 2012 2. Analyze drill performance data and establish a performance baseline if possible; define data collection procedure – FFY 2011 and continuing 3. Ascertain availability of replacement parts – FFY 2011 4. Complete operating and maintenance instructions and enter into database – FFY 2011 5. Complete/update drawings and enter into database – FFY 2011 6. Perform general maintenance and repairs – ongoing and as needed 7. Manufacture second system – FFY 2012

Koci Drill – The drill, named after the late drilling engineer Bruce Koci, is an electromechanical, single-barrel, coring drill designed to operate in ice containing rock and silt. The system includes cutters with replaceable carbide inserts for drilling in rocky/silty ice. A non-coring rock bit and auger is used for penetrating large rocks and gravel. The drill bit is rotated via a rigid drill string by a surface-mounted electric motor mounted to a tower. Drill penetration is controlled by a feed system on the drill tower to account for varying ice/rock conditions. The drill produces 76-mm (3-inch) diameter cores a few tenths of a meter long. It was tested and used to collect scientific samples in Beacon Valley in the 2006-07 Antarctic field season and again, after repair and modification, in the 2008-09 and 2009-10 field seasons

Current Status:	The Koci Drill is the only drill of its type and is under continued development. The drill was used successfully in Beacon Valley during the 2009-10 field season; it has not been used since.
Technical Issues:	Performance Data – Because of the nature of the ice being drilled and the fact that conditions can vary drastically from hole-to-hole in a matter of a few meters, it will be difficult to collect anything but general performance data for this drill. Documentation – Drawings for the drill have been produced and are entered into the database as are the results of the testing of the drill; operating and maintenance procedures have not yet been written. Other – The drill relies on flights to move ice chips and a downhole vacuum cleaner to remove rock chips and loose silt. Rock cutting is difficult and could be better accomplished with a drilling medium (probably air), but logistical and environmental constraints limit options.
Plans:	1. There are no plans at present to repair or continue development of the Koci Drill. Substantial improvement in drill performance in very rocky ice would require a different type of drill and it is unclear whether the development of a new drill is warranted. The Koci Drill could be repaired and modestly modified if a project eventuated in which the PIs were content with the type of performance of which the Koci Drill is capable. We believe that a proposal for its use has been submitted to NSF.

Portable Hot Water Drills – These drills use hot water to create shallow holes in the ice; they are non-coring. Primary use is for shot holes for seismic work, but they have been used also for access holes through a thin ice shelf. These drills are transportable by light aircraft and helicopter.

Current Status:	IDDO has two portable hot water drills; one is currently assigned to a project for the next two years. Several inquiries have been received for projects requiring hot water drills.
Technical Issues:	Performance – Reliable and efficient to a depth of 25-30 m Documentation – Approximately 75 drawings exist in the document control database, but documentation for the drills is incomplete. Other – Hot water drills are expandable to create larger and/or deeper holes. They can also, to some degree, be modularized so components can be added and subtracted to create a system to meet a particular project's needs. IDDO hopes to standardize and modularize a basic portable hot water drill so one or more could be used as needed.
Plans:	1. Standardize and modularize drill – probably not earlier than FFY 2013 and when funding is available. After that: 2. Complete operating and maintenance procedures –FFY 2013 3. Develop procedure for preparing drills for issue – FFY 2013 4. Complete documentation and enter into database – FFY 2013



Rapid Air Movement (RAM) Drill – The RAM drill was developed for a particular seismic program. It is a system in which high-velocity air drives rotating cutters and blows the ice chips from the hole. The cutting drill motor hangs on a hose that carries the air from the surface and is reeled out as the hole deepens. In typical firn/ice conditions in West Antarctica two compressors in parallel are needed to provide enough air flow to overcome air losses in the firn. It has been used three times in West Antarctica, most recently during the 2009-10 field season, when it routinely attained depths of 90 m. It has been tried out once in East Antarctica with lesser success (see "Current Status" box).

The RAM drill is limited to a maximum depth of 95 m by the amount of hose that can be carried on the current configuration of its hose reel (one hose-width wide, no level wind), but in principle it could drill much deeper; once the penetration is below the firn/ice boundary there is no additional loss of return air and greater depths should come relatively easily. Factors affecting the drilling through the firn to the firn/ice boundary, however, are not well understood and methods of drilling consistently to below the firn/ice boundary remain to be found. Once those methods are discovered, this drill, outfitted with a standard hose reel and level wind, could likely be a valuable tool for rapidly accessing depths that would be limited only by hole closure -- hundreds of meters or even a thousand, depending on englacial temperatures. This drilling technology shows promise as a partial solution to the community request for Rapid Access Drilling.

Current Status:	While the drill worked well during the 2009-10 season, additional modifications are needed to make the drill more reliable on longer traverses. IDDO has not repaired the drill since the 2009-10 season.. The Askaryan Radio Array (ARA) project, funded by OPP, borrowed the drill for the 2010-11 Antarctic field seasons to test methods of producing 200-meter holes for radio antennae at South Pole, but could not get deeper than 63 m, so have expressed no further interest in the RAM Drill.
Technical Issues:	Performance Data – The performance of the RAM drill is well documented for the three seasons for which it was used for seismic projects. However, drill performance appears to be very sensitive to the local characteristics of the firn being drilled; this is not well understood. Documentation – Documentation for the drill is partially complete in that drawings for the hose reel and its sled and the drill sondes have been completed; these need to be added to the SSEC document control database, however. Material lists and several drawings exist for the compressor packages; “as-built” drawings should be completed. Operating and maintenance instructions need to be completed. Other – The loss of air in firn needs to be better understood and techniques or equipment developed to minimize losses and, hence, the number/size of compressors needed. The hose reel presents logistical problems and should be replaced before use on any more seismic traverses.
Plans:	The following plans for the RAM drill will be implemented only in the event of a demand for the drill; they would require considerable time and effort. 1. Investigate means of sealing off the firn to prevent air loss 2. If necessary, perform study with the aid of appropriate research scientists to better understand and quantify air losses in firn 3. Make needed modifications, including new hose reel and modifications to compressors to improve traversing

DISC Drill

The Deep Ice Sheet Coring (DISC) Drill developed by Ice Coring and Drilling Services (ICDS) under contract with the US National Science Foundation is a tilting-tower electromechanical drill designed to take 122 mm diameter ice cores to depths of 4000m with variable core lengths up to a design limit of 4 meters. The drill is currently able to recover cores up to 3.5 meters. The DISC Drill consists of four major mechanical drilling subsystems and several supporting on-surface activities. The mechanical drilling subsystems are a drill sonde, a drill cable, a tower, and a winch. Critical on-surface activities are core-handling, screen-cleaning, and drill-fluid handling. This drill system is currently at WAIS Divide in Antarctica and has been used there for four production seasons. The drilled depth as of February, 2011, is 3331 meters.

The DISC Drill system design is a dynamic process, and it is going through continuous modifications and enhancements. The major modifications undertaken during FFY2010 in preparation for the 2010-11 field season were: control software upgrades, new motor driver boards in the instrument sections, an ethanol-water solution delivery module and a core barrel warming bath for use if warm ice was encountered during drilling, new seal material for the motor pump sections and a permanent level-wind tracking device to replace the prototype assembly that was successfully tested the previous season. IDDO also performed all necessary maintenance and repair of the system's components. The majority of the modifications were successfully tested at WAIS Divide during the 2010-11 field season, although the motor driver boards required extensive revamping on site. The ethanol-water delivery module and the core barrel warming bath were not tested, as warm ice was not encountered during the season.

The Long Range Science Plan 2011-2021 indicates that, after the work with the DISC Drill at WAIS Divide, including the replicate coring has been completed, the drill will next be assigned to a drilling site in East Antarctica. This means that the drill will have to operate at down-hole temperatures at least as cold as -50C and perhaps as cold as -58C. During FFY 2012 IDDO will evaluate the ramifications for the DISC Drill of operating at such cold temperatures (and perhaps altitudes approaching 4000 m). Included in this evaluation will be not only how the drill needs to be modified to work at such low temperatures, but the whole question of finding a new drilling fluid (see section "Drill Fluid," below).

Current Status:	The DISC Drill is being used for the WAIS Divide drilling and modifications and repairs are made to the drill between the field seasons.
Technical Issues:	Performance Data– Data are being collected while the drilling progresses at WAIS Divide. These data provide information useful in making modifications to the drill that will improve its performance. Data gathered on subsequent DISC Drill projects will be used in a similar way. Documentation – The DISC Drill is being documented as it is being developed. IDDO makes use of an Engineering Change Notification process to ensure that documentation is updated to reflect changes to the equipment. Documentation is maintained in the SSEC Documentation database. Other – The obsolescence and the resulting inability to get replacement components – particularly electronics – is an ongoing challenge that will be faced during the usable lifetime of the drill. A new drill fluid will need to be selected for the DISC Drill prior to the next field project; in East Antarctica the drill fluid would have to retain a low viscosity at very low temperatures.
Plans:	1. Make modifications and general repairs identified during 2010-11 field season -- FFY 2011 2. Determine components that need to be replaced to make the drill ready for East Antarctica and test components as necessary – FFY 2012 and FFY 2013 3. Modify DISC Drill for use at high, cold sites in East Antarctica – after FFY 2013 4. Develop plan for continuous upgrading of drill system, including the upgrade to drill at -55ºC; requires decision from IDPO/SAB on future use of DISC Drill – FFY 2012

Replicate Coring

Taking a single deep ice core from a given region makes replication and verification of the validity and spatial representativeness of key results difficult. Furthermore, scientific demand for ice samples has been and will continue to be very unevenly distributed, with the ice core archive being completely depleted in depth intervals of high scientific interest, whereas in other intervals more than 50% of the ice remains. The ability to obtain additional volumes of ice sample in selected intervals, termed replicate coring, will address these concerns and add value to the scientific return from ice coring. It is important that the taking of replicate cores not compromise other scientific activities, in particular borehole logging.

The design of a replicate coring system for the DISC Drill incorporates as its essential concept the tilting and forcing of the sonde against the drill hole wall by "actuators" that push against the wall upon command from the surface. Drilling then gradually deviates out of the main borehole into the wall. The replicate coring system is under construction; some tests of portions of the system have been carried out.
The first field testing of the replicate coring system is expected to occur at WAIS Divide in the latter part of the 2011-12 field season.

Current Status:	Fabrication of a replicate coring system for the DISC Drill is progressing. It is anticipated that the system will be ready to recover replicate cores beginning in the 2011-12 field season at WAIS Divide.
Technical Issues:	Performance Data – There are no performance data on replicate coring. Documentation – All work on the replicate coring system is being documented according to SSEC standards and archived in the control document database. Other – While the Russians have successfully deviated their boreholes around stuck drills, no one has developed a system specifically to replicate ice cores at any chosen depth within an existing borehole.
Plans:	1. Complete fabrication of replicate coring system for use with DISC Drill – FFY 2011 2. Test system in deep borehole at WAIS Divide – FFY 2012 3. Make necessary repairs and modifications to system -- FFY2012 4. Production replicate coring season at WAIS Divide -- FFY 2013

Drill Fluid

With the phase-out and banning of production of ozone-depleting substances such as chlorofluorocarbons, a good substitute for the two-part drilling fluid used at WAIS Divide and a number of European drilling projects is a necessity for the continuation of intermediate and deep coring projects. A few possible substitutes have been identified: n-butyl acetate, dimethyl siloxane (silicone) oil, and an ESTISOL-COASOL mixture. Butyl acetate has been used by both the US and the Japanese programs in the past, but because of the health risks associated with the chemical, ICDS and the US science community decided to abandon its use at the start of the WAIS Divide Ice Core Project (WDICP). ESTISOL-COASOL is being used in the NEEM Project in Greenland; the mixture has a disadvantage in that ESTISOL, a coconut extract, could compromise biological experiments because it is a nutrient. Silicone oils have been suggested as a possible ice drilling fluid but have not been used; the oils have had a disadvantage in that they are difficult to remove from surfaces. However, members of the TAB have indicated that silicone oils are now available that do evaporate cleanly from ice surfaces and that the Chinese are planning to use one as a drilling fluid in the East Antarctic interior. Both the silicone oils and the ESTISOL-COASOL mixture have the major disadvantage of being much more viscous at low temperatures than either n-butyl acetate or the Isopar K-HCFC 141b mixture used at WAIS Divide.

In 2003, ICDS undertook a study to identify a drilling fluid for WDICP (Drilling Fluid Observations and Recommendations for U.S. Polar Program, WAISCORES Drilling Project, ICDS, 2003). A number of laboratory experiments were undertaken, but the study was not completed before the decision was made to use the Isopar K-HCFC 141b mixture. With the drilling of both deep and intermediate depth holes in very cold regions in East Antarctica a likely prospect in the future, IDDO will resume ICDS' study of drill fluids. The FFY2012 budget will include funding for a search for an appropriate drilling fluid.

Current Status:	While there are currently available drilling fluids, none are ideal for drilling at very cold sites.. Several papers have been published about potential new fluids and the Europeans are reportedly beginning a new study for a suitable drilling fluid.
Technical Issues:	Fluid should, among other things, be non-hazardous, have low viscosity at very low temperatures, and not inhibit or complicate biological studies.
Plans:	1. Define the science requirements for a new drill fluid; IDDO will oversee the project – FFY 2011-12 2. Explore possibility of collaborating with Europeans on the development of a drill fluid; IDDO will supervise and subcontract the project if needed – FFY 2011 3. Conduct drill fluid study – FFY 2012

Intermediate Drill

Many of the coring objectives given in the Long Range Science Plan, such as those in the IPICS 2k array and 40k network, are attainable in many locations with an intermediate-depth drill, meaning one that can collect core from a fluid-filled hole down to depths of 1000 - 1500 meters. IDDO does not at present have an intermediate-depth drill, but the need exists and planning for one has begun. Science requirements have been agreed to and an initial feasibility study has been completed. The current plan is to work cooperatively with the Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, in modifying their existing Hans Tausen intermediate depth drill to produce two copies of a new drill, one for the Danes and one for IDDO

Current Status:	IDDO is currently in the midst of planning for the development of an intermediate depth coring drill. A conceptual design has been prepared and preliminary estimates of cost, size, and extent of required logistical support made.
Technical Issues:	Contrary to the plan in the 2010 Drilling Technology Plan, the capability for replicate coring will not be included in the drill, so as to keep the drill simple and speed its development. Because a drill fluid is needed to keep the borehole open, suitable fluids must be identified for the drilling locations anticipated.
Plans:	1. Start design - beginning of FFY 2012. 2. Complete design and begin fabrication of drill – FFY 2013 3. Complete fabrication; field test in Greenland; prepare drill for 2014-15 scientific drilling – FFY 2014 4. Deploy drill to Antarctica-- FFY 2015

Hot Water Rapid Access Drills

When an ice core is not needed, a hot water drill can provide fairly rapid access to the base of an ice sheet where it is relatively thin. Such a drill is particularly useful for drilling through an ice shelf to enter the ocean beneath. IDDO does not at present have a field-ready hot water access drill. ICDS (IDDO's predecessor) received the Kamb-Engelhardt hot water drill (KE drill) from Caltech in 2002. It had been used successfully to drill many holes, some as deep as 1000 m, to the bed of the West Antarctic ice sheet in the region of the Ross Embayment ice streams. However, it has been idle since its last deployment (~1998); despite 'mothballing', it would require extensive and critical inspection and probably a great deal of repair and upgrading to be fit for Antarctic service.

IDDO has recently been asked to provide an access hole through an Antarctic ice shelf, so it is planning to regain that capability, either by refurbishment of the KE drill or by constructing a new drill.

Current Status:	The KE hot water drill is in IDDO inventory, but would require extensive updating; also, its condition would need to be evaluated and a decision made as to how much of the drill could be salvaged for use.
Technical Issues:	Performance History – The KE drill has a long record of successful performance. Hot-water-drilling thermodynamics and heat transfer are well known; it is possible to predict the performance of a particular drill configuration by calculation. IDDO would institute a process for logging all relevant data in operating the drills. Documentation – A description of the KE drill and its operation exists. Other – If the drill is to be used in the future to access the bed of grounded ice, the degree of cleanliness of the drill water and any instruments to be deployed will need to be defined.
Plans	1. Evaluate the relative merits of refurbishing the KE drill v. constructing a new drill and decide which way to proceed– FFY 2011. 2. Complete design and fabrication of the hot water drill– FFY 2012 & FFY 2013 3. Deploy drill in Antarctica -- FFY 2014

Mechanical Rapid Access Drills

As a by-product of their operation, ice-coring drills (ICDs) produce semi-permanent boreholes in which various properties of the surrounding ice can be determined using geophysical logging methods; the uniform hole diameter produced by ICDs facilitates these measurements. Geophysical measurements in ICD holes currently include borehole ‘tilt’ and closure, high-precision temperature, sonic velocity, and optical scattering/absorption. These logs provide valuable information about how horizontal velocities, shear-strain rates, temperature, ice fabric, dust concentration, and entrained sediment vary from the bed to the surface of an ice sheet. This information can in turn be used to improve the understanding of ice rheology, regional ice dynamics, ice-bed interactions, climate history, and geothermal flux. Short bedrock cores have also been obtained with ICDs, although ICDs were not really designed with this in mind. But ICDs are both slow and expensive to operate, limiting the ability to obtain these types of glaciological, geologic, and paleoclimatic data to just a few sites in the polar regions. In addition, the sites selected for ICD holes are rarely the best locations for geologic and many other studies. Finally, conditions in and around ICD boreholes are not ideal for some types of geophysical measurements such as high precision temperature.

The science behind core drilling does not necessarily require continuous cores from the ice sheet surface. As cores covering the last 100k years of earth history become more numerous, the option of obtaining rapid access to depths below which older ice can be cored becomes increasingly attractive.

The limitations inherent in current deep drilling systems indicate the need for a mechanical drill that can provide rapid access to depths of 1–4 km. The new drilling system should be able to produce arrays of semi-permanent, uniform-diameter holes with minimal thermal disturbance, allowing a wide range of experiments to be conducted within each borehole over a number of years. It should also be capable of allowing access at depth to an ICD that can acquire continuous cores of usable diameter at greater depths and of sampling sub-ice basal materials (at least where environmental conditions permit). The system should be both modular and flexible so that new tools can be easily added to satisfy future research needs.

The Long Range Science Plan cites many scientific objectives that would benefit from a rapid-access mechanical drill, but they can generally be divided into two categories -- those that require only a hole and those that aim at the recovery of ice from a large depth. The former, which involve either logging of the hole or the emplacement of instruments within the hole or the subglacial bed, can be attained with a hole of small diameter – 3" is commonly cited. For the latter, on the other hand, especially since the targeted ice will be of special interest, a core diameter of at least 4" probably will be called for, which in turn means a hole diameter of at least 5". That scales up the amount of ice that needs to be removed, hence the power consumed, the amount of fluid needed to fill the hole, and other factors that scale as the volume of the hole, by a factor of approximately three. The logistical implications of this scaling are at least qualitatively apparent.

IDDO will evaluate the feasibility, cost, and logistic burden of rapid access concepts, including drilling into, or otherwise sampling, the subglacial bed, keeping the dichotomy just outlined in mind. Also related in the general concept of rapid access are the capabilities of large diameter hot-water drilling.

Current Status:	No mechanical rapid access drills capable of drilling to 1-4 km exist. Clow and Koci (*Memoirs National Institute Polar Research, Special Issue* 56, 5-37, 2002) have suggested the use of coiled tubing technology, which has been used in the petroleum industry, to drill rapidly to these depths. Conventional mineral drilling rigs can use straight pipe (rods) from the surface with automated joint make-and-break; TAB members suggested jointed pipe rigs as a good starting point for the polar regions,
Technical Issues:	A drill fluid is needed to keep borehole from closing. Logistical burden for even small diameter holes is non-trivial and access for coring may be prohibitive. Minimum core diameter usable by interested scientists should be explored by IDPO & SAB

Plans:	1. Define science requirements for feasibility study – FFY 2012 2. Evaluation of feasibility and conceptual design of mechanical rapid access drills – FFY 2012 – FFY 2013 3. Design mechanical rapid access drills as appropriate – FFY 2013 – FFY 2014 4. Fabricate mechanical rapid access drill – FFY 2014 - 2015 5. Test drill in Greenland -- FFY2015 6. Deploy drill to Antarctica– FFY 2017

Logging Winches

The IDPO-SAB recommended that IDDO purchase or develop two logging winches and make them available for use by the science community. The first, and higher priority, is a 1-km winch which would be the more portable and used on shallow and intermediate depth holes. The second is a winch capable of logging to 4 km.

Current Status:	The logging community has prepared a white paper that can be used for guidance in procuring the logging winches. IDDO personnel have also done preliminary searches for the availability of logging winches. IDPO-IDDO have arranged for the transfer of the IceCube logging winch to IDDO; it has the capability of logging to depths of more than 2500 m.
Technical Issues:	Performance History – None; users such as Gary Clow and Ryan Bay should be contacted regarding their experience with various types of winches. Documentation – Documentation for the winches would be developed and entered into the document database as they are purchased and modified. Other – Experience of Gary Clow and IceCube indicates that off-the-shelf winches require a substantial amount of modification to be useful and reliable for logging ice boreholes. The suitability of the IceCube logging winch for deep boreholes needs to be determined; e.g., is the depth capability sufficient.
Plans:	1. Develop science requirements for logging winches – FFY 2012 2. Purchase and modify if necessary a 1-km winch – FFY 2013 3. Deploy winch to Antarctica -- FFY 2014 4. Acquire and refurbish/modify, if necessary, IceCube logging winch – FFY 2012

RESPONSES TO DIRECTIVES FROM THE LONG RANGE SCIENCE PLAN

IDDO notes the following guiding principles for development of drilling technology expressed in the IDPO Long Range Science Plan 2011-2021:

"1. Designs should be such that the supporting logistical requirements do not impede completing the science goals;

2. Science requirements need to be balanced by consideration of logistics including weight, size, costs and time frame for development. All factors need to be clearly defined at the initial stage of planning, and changes during the engineering design and fabrication process should be reassessed by the IDPO;

3. Drills and accompanying technology for a specific project should be developed with consideration of potential use in future possible projects. They should be versatile and adaptable;

These principles have been and are being adhered to in the course of IDDO's major development projects -- the design and construction of replicate coring capability, the design and construction of the large-diameter "Blue Ice" drill, and the designs for the new intermediate depth drill.

4. The next generation of ice coring and drilling scientists and engineers should be trained.

Except for two senior managers, all of our engineering staff are under 40 -- they are the next generation! We are more concerned about the next generation of contract drillers, and have so far identified a few likely replacements.

Recommended technology investments

The IDPO Science Advisory Board identified the following high-priority investments in drilling technology that are needed to achieve the planned science goals:

1. Maintain and extend the existing agile coring/drilling capabilities, including addition of clean, easily transportable hand and shallow coring devices;

A major focus of this Plan -- see pp. 4 - 16

2. Purchase/construct two bore-hole logging winches: first priority is a 1-km winch; second priority is a 4-km winch;

The specific requirements for a logging winch are still a matter of discussion in the logging community -- see box on p. 24

3. Finish development of replicate coring capability; progress on this task is well underway for the WAIS Divide project;

A major focus of current IDDO activity -- see pp. 18 - 19.

4. Purchase/construct a versatile intermediate-depth (1000-1500 m) ice coring drill. This project is now in the initial stages of planning;

A feasibility study for the intermediate depth drill, including sizes and cost estimates, has been completed; if funding is available work on design and construction will commence at the start of FFY 2012 – see pp. 20 - 21.

5. Design and develop drills that will allow rapid access to the base of ice sheets. Holes of different diameter are needed for specific projects, and modular designs are preferable;

This project is still some years in the future; current plans call for beginning feasibility studies in FFY 2012. See pp. 21-24.

6. Identify upgrades to the DISC drill that would allow it to be used in cold conditions in East Antarctica;

Identification of the needed upgrades will begin next year -- see pp. 17 - 18.

7. Design and develop methods and protocols for clean access for sampling of sub-glacial environments;

Such a design is well advanced, but IDDO has no plans to access the environmentally sensitive bed of the grounded ice.

8. Identify a drilling fluid that is environmentally acceptable and can be used at temperatures down to -55°C.

This is a matter under discussion with the Technical Advisory Board; some promising approaches have been found. Identification of the needed upgrades will begin next year -- see pp. 19 – 20.

FIELD SUPPORT OF SCIENCE PROJECTS

In addition to the development of new and existing ice drilling and related equipment and its maintenance, IDDO will continue to provide support for science projects in the field. This support generally consists of providing the drilling equipment for the project, assisting the PIs with planning the field activities, and providing a field crew for the operation of the equipment.

Field projects are usually one or two seasons long and are usually defined only a year or two prior to their execution. Typically, during a fiscal year IDDO might have five or six projects being actively supported with half of them actually in the field and the other half in the planning/preparation phase of the project. Below, known projects for the next several years are discussed.

WAIS Divide Ice Core Project

IDDO will continue drilling with the DISC Drill system at WAIS Divide in Antarctica during the 2011-12 season.

FFY 2011 – The 2010-11 field season was especially challenging because of some problems with the drill; nevertheless, the target depth of 3330 m was attained. No difficulties associated with warm ice were encountered;, the temperature at the final depth was estimated to be -10ºC , 7º below the pressure-melting point).

FFY 2012 – IDDO will support the logging activities in the WAIS Divide hole during the 2011-12 field season. At the start of the season there will be an evaluation of the thickness of ice still below the borehole; if there is enough ice, regular coring will resume for an additional depth to be determined on site. When the core drilling is done, borehole logging will commence. IDDO expects to be asked by some logging PIs to help with their activities and stands ready to do so as requested and approved by OPP and IDPO. Following the logging, preparations for replicate coring will be completed and initial replicate coring operations will be undertaken.

FFY 2013 – During the 2012-13 field season, IDDO expects to complete replicate coring in the WAIS Divide hole. Preliminary plans called for replicating approximately 12.5% of the core (~415 meters). Inasmuch as the fabrication of the replicate coring system has not yet been completed, the details of the replicate coring objectives – whether, for example, sampling is to be done at selected intervals down the entire length of the hole, or only in the deepest part of the hole -- are not yet decided. IDDO will also assist with additional borehole logging if requested and approved.

Shallow Coring and Drilling Projects

Support of NSF shallow coring and drilling (400m or less) single-investigator or small group projects in the Arctic and the Antarctic and on lower latitude ice sheets and glaciers is an important ongoing activity of IDDO. IDDO will continue to support these projects in much the same manner as done in the past. The involvement of IDDO with a project will begin in the proposal phase, in which IDDO and IDPO will work with the PI to understand the objectives of the project and to determine how best to support it. Once NSF has notified IDPO that it will support a project, IDDO, IDPO, and NSF together will decide on the appropriate means of funding of IDDO's participation. The close collaboration of the researchers and IDPO/IDDO is the key to success and upon approval of a project, IDDO will work closely with the principal investigators to define project requirements more fully and prepare a project plan, which will be followed in the conduct of the project. Support of the project will not be limited to the field, but will also entail assisting the PI in planning for IDDO support and in the special preparation of equipment, if necessary. At the end of each project, the PI will be asked to provide feedback on the successes attained and difficulties encountered in the course of the work.

FFY 2011 – IDDO supported four shallow coring and drilling projects in Antarctica during the 2010-11 field season and is supporting two others in Greenland and Alaska. In addition, IDDO provided support to four investigators by issuing hand augers or a small hot water shot hole drill to them.

FFY 2012- 2020 --IDDO will continue to support science projects approved by OPP.

Preserving Ice Core Boreholes for Logging Science

The Long Range Science Plan points out that the casings in the boreholes at GISP2, Siple Dome and Taylor Dome are in danger of collapsing. Direct visual evidence of serious damage to the casing in the GISP2 borehole at Summit, Greenland is available; it is likely that the similarly emplaced casings in the younger bore holes on Taylor and Siple Domes in Antarctica will become vulnerable to similar damage. Much science remains to be carried out in these boreholes if access is preserved.

FFY 2012 -- IDDO will undertake evaluation of the situation in the GISP2 borehole and, as staff time permits, begin to develop a plan for the restoration of unimpeded access to it

FFY 2013 -- IDDO will complete the plan for the GISP2 borehole, and implement it during the summer field season at Summit

FFY 2014 -- IDDO will seek opportunities to evaluate the situations at Taylor Dome and Siple Dome

Succeeding years -- IDDO will complete any needed work at Taylor and Siple Domes as access to the sites becomes available.

Subglacial Access

As mentioned in the section Hot Water Rapid Access Drills, IDDO is planning either to refurbish the Kamb-Engelhardt drill or to design and build a new hot water drill to provide subglacial access through relatively thin ice.

FFY 2012-13 -- If the relevant science proposal is funded, design and fabrication of the hot water access drill will proceed**.**

FFY 2014 – IDDO plans to deploy the drill to Antarctica for use during the 2013-14 field season.

FUNDING

The target budget levels provided by NSF of IDDO under the cooperative agreement are

FFY 2009	$2,505,919
FFY 2010	2,600,916
FFY 2011	2,696,840
FFY 2012	2,799,545
FFY 2013	2,900,124
	--------------- -
Total	**$13,503,346**

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Ice Drilling Design and Operations
Appendix 1
Science Projects Matrix

		PROJECTS																				
		DISC Drill modifications	**WAIS Divide drilling**	**Replicate development**	**Replicate drilling**	**DISC modifications for East Antarctica**	**East Antarctica deep drilling**	**Logging winch development**	**Shallow drilling projects**	**Agile drill maintenance**	**Preserve ice core boreholes**	**Hot water subglacial access drill development**	**Hot water subglacial access drilling**	**Blue Ice Drill development**	**Blue Ice Drill drilling**	**Mechanical rapid access drill development**	**Mechanical rapid access drilling**	**Intermediate depth drill development**	**Intermediate depth drilling**	**RAM Drill modifications**	**RAM Drill drilling**	**Drill fluid development**
SCIENCE	**Climate**																					
	200 yr arrays								x	x												
	2k arrays			x	x			x	x	x	x							x	x			
	40k network	x	x	x	x	x	x	x			x					x	x	x	x			x
	Last interglacial			x	x	x	x		x		x					x	x					x
	Prior to 800k yrs			x	x	x	x	x						x	x	x	x					x
	IPICS oldest ice				x	x	x	x						x	x	x	x					
	Ice Dynamics & Glacial History																					
	Basal conditions & geothermal flux							x			x	x	x			x	x			x	x	
	Seismic basal conditions detection																			x	x	
	Sub-ice shelf mass balance											x	x									
	Grounding zone processes											x	x			x	x					
	Rheological properties of ice		x		x		x	x			x					x	x					
	Glacial history											x	x									
	Conditions at ice sheet bed											x	x			x	x					
	Sub-Ice Environment																					
	Sedimentary record											x	x			x	x					
	Microbial ecosystems & biogeochem											x	x			x	x					
	Geologic & tectonic history											x	x			x	x					
	Subglacial lakes & hydrology											x	x			x	x					

Appendix 2
Long Range Project Schedule

X - Planned ; Y – Available for Use			**PROJECTS**																				
CALENDAR YEAR	**QUARTER**	**Number of Projects**	**DISC Drill modifications**	**WAIS Divide drilling**	**Replicate development**	**Replicate drilling**	**DISC modifications for East Antarctica**	**East Antarctica deep drilling**	**Logging winch development & use**	**Shallow drilling projects**	**Agile drill maintenance**	**Preserve ice core boreholes**	**Hot water subglacial access drill development**	**Hot water subglacial access drilling**	**Blue Ice Drill development**	**Blue Ice Drill drilling**	**Mechanical rapid access drill development**	**Mechanical rapid access drilling**	**Intermediate depth drill development**	**Intermediate depth drilling**	**RAM Drill modifications**	**RAM Drill drilling**	**Drill fluid development**
2011	1	9		x	x					x	x		x			x			x				x
	2	8	x		x					x	x		x		x				x				x
	3	10	x		x				x	x	x	x	x		x				x				x
	4	10		x		x			x	y	x	x	x			x			x				x
2012	1	9				x			x	y	x	x	x			x			x				x
	2	11			x		x		x	y	x	x	x				x		x		x		x
	3	11			x		x		x	y	x	x	x				x		x		x		x
	4	9				x			x	y	x	x	x				x		x			x	
2013	1	9				x			x	y	x	x	x				x		x			x	
	2	8					x			y	x	x	x				x		x		x		
	3	8					x			y	x	x	x				x		x		x		
	4	9					x		x	y	x	y		x			x		x			x	
2014	1	9					x		x	y	x	y		x			x		x			x	
	2	5					x			y	x						x			x			
	3	**5**					x			y	x						x		x				
	4	5					x			y	x			y			x			x			
2015	1	6					x			y	x			y			x			x			
	2	4					x			y	x							x					
	3	4					x			y	x							x					
	4	5						y		y	x						x			x			
2016	1	5						y		y	x						x			x			
	2	3								y	x						x						
	3	2								y	x												
	4	4								y	x							y		y			
2017	1	4								y	x							y		y			
	2	2								y	x												
	3	2								y	x												
	4	2								y	x												
2018	1	2								y	x												
	2	2								x	x												
	3	2								x	x												

ACRONYMS

ARA: Askaryan Radio Array

BFC: Berg Field Center

DISC: Deep Ice Sheet Coring

DVD: Digital Video Disk

FFY: Federal Fiscal Year

HCFC: Hydrochlorofluorocarbon

ICD: Ice-coring Drill

ICDS: Ice Coring and Drilling Services

IDD: Intermediate-Depth Drill

IDDO: Ice Drilling Design and Operations

IDPO: Ice Drilling Program Office

ITASE: International Trans-Antarctic Scientific Expedition

KE: Kamb-Engelhardt

LISSARD: Lake and Ice Stream Subglacial Access Research Drilling

NSF: National Science Foundation

OPP: Office of Polar Programs

PI: Principal Investigator

PICO: Polar Ice Coring Office

RPSC: Raytheon Polar Services Company

RAM: Rapid Air Movement

SAB: Science Advisory Board

SIPRE: Snow, Ice and Permafrost Research Establishment

SSEC: Space Science and Engineering Center

UNH: University of New Hampshire

WAIS: West Antarctic Ice Sheet

WDICP: WAIS Divide Ice Core Project