BLUE ICE CORE QUALITY FEASIBILITY STUDY

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PURPOSE

In the National Science Foundation Ice Drilling Program’s (IDP) 2024 Long Range Science Plan, IDP was tasked with conducting an engineering feasibility study to evaluate and recommend long-term drilling approaches for retrieving high-quality ice cores down to a depth of 400 meters in Blue Ice Areas (BIAs). As outlined in the 2024 Long Range Drilling Technology Plan, IDP's responsive action is as follows:

“In 2024, through an iterative process with IDP and community scientists, IDP engineers are evaluating a number of known and promising technologies and approaches and will outline the pros and cons of each. A report will be drafted to help inform future development of the appropriate technology.”

This report summarizes the results of this action.

INTRODUCTION

Drilling in ice without the use of a borehole fluid can be achieved to depths of 300-350 meters before risking borehole closure. However, the ice cores extracted from depths exceeding 150-180 meters often exhibit very poor quality (Talalay, 2016, pp. 109-110). IDP has largely found this to be true, except when drilling at the Allan Hills in Antarctica, a Blue Ice Area, where core quality deteriorates at depths as shallow as 50 meters.

The exact reasons for this deterioration at shallower depths in BIAs compared to non-BIAs are not fully understood. IDP engineers have a few theories that are listed below. We welcome input from the science community on the validity of these theories.

- The leading theory within IDP is that the absence of a firn layer in BIAs causes the overburden pressure to increase more rapidly with depth compared to non-BIAs, which have a surface layer of low-density firn up to 100-meters thick.
- The unique ice layer folding in certain BIAs, such as at the Allan Hills, may increase internal stress in the ice sheet, causing cores to fracture more easily when exposed to ambient pressure.
- BIAs may exhibit larger ice crystal size than non-BIAs, which may increase the cutting force required by the drill and thus may increase the mechanical stress imposed on the core.

It should be noted that IDP has experience recovering ice cores from greater than 50-meter depths at only two BIAs: Taylor Glacier and the Allan Hills. A search for other groups that have drilled ice cores in BIAs revealed the following three projects:

1. Yamato Mountains, Antarctica – 101-meter depth – Japanese Antarctic Research Expedition – 1983

2. Scharffenbergbotnen, Antarctica – 52-meter depth – 1997/1998

3. Mount Moulton, Antarctica – 30-meter depth – 2003/2004

For each of these projects, no information was found on the quality of the ice cores or the drilling methods used.

The remainder of this report details several solutions that IDP has proposed to improve core quality in BIAs, along with the advantages and disadvantages of each. Before discussing these solutions, the report reviews how core quality is defined, the past performance of IDP's shallow drills, and lessons learned from drilling in non-BIAs.

CORE QUALITY DEFINITION

Currently, IDP uses the following scale to assess the minimum core quality requirements for projects:

1. **Excellent** – Single piece, no breaks
2. **Good** – Two pieces, single break
3. **Fair** – Three pieces, two breaks
4. **Poor** – Four or five pieces
5. **Very Poor** – More than five pieces, rubble

IDP engineers have identified several limitations with this scale:

1. It does not account for surface and internal fractures.
2. It does not consider the minimum piece length required for scientific analysis.
3. Cores of significantly different quality can receive the same score. For example, a 1-meter core with 90 cm of intact ice and 10 cm of rubble receives the same score as a core that is entirely rubble.

An alternative scale has been presented in literature (Souney, 2021), and is repeated here for reference:

1. **Excellent** – 0 to 1 break / no fractures
2. **Very Good** – 0 to 2 breaks / 90% no fractures
3. **Good** – 0 to 3 breaks / 50% no fractures
4. **Fair** – greater than 10 cm without fractures
5. **Poor** – greater than 10 cm without through fractures
6. **Very Poor** – less than 10 cm without through fractures

To standardize how drillers record core quality in the field, IDP is updating core log templates to facilitate the capture of useful information. The updated template is shown below with 2 example drill runs (Table 1).

Run #	Start Depth [m]	End Depth [m]	Drilled Length [cm]	Recovered Length [cm]	Longest Piece [cm]	# Pieces >10 cm	Options	Surface	Core Usable
45	101.5	102.5	100	98	90	1	C S **W** R	0	Yes
46	102.5	103.5	100	103	20	3	C **S** W **R**	2	No

Key:

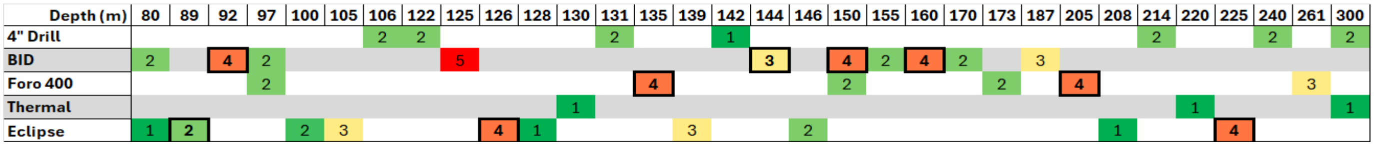
- **Options:** C = core dog drag marks; S = spall; W = wafering; R = rubble
- **Surface:** 0 = no visible cracks; 1 = microcracks; 2 = deep and/or through cracks
- **Core Usable:** Yes = the sample meets project specific requirements and can be used for analysis; No = the sample does not meet project specific requirements and cannot be used for analysis

Table 1: Updated core log template for IDP drillers to record core quality in the field.

CORE QUALITY OBTAINED IN PAST IDP SHALLOW DRILLING PROJECTS

A review of the end-of-season reports from IDP's previous shallow core drilling projects was conducted and the results are presented in Figure 1. Each borehole was assigned a core quality score from 1 to 5 based on details from the driller's end-of-season report and Principal Investigator feedback. It was noted during this review that there is no standardized method for recording core quality in the field, so these results should be interpreted with caution.

Despite this, it is evident that cores drilled at the Allan Hills (indicated by the cells bordered in black) have significantly worse quality than cores drilled by the same system to similar depths in non-BIAs. Another notable finding is that IDP's Thermal Drill has consistently achieved excellent core quality in every project it has been used on, even at depths of up to 300 meters.



Depth (m)	80	89	92	97	100	105	106	122	125	126	128	130	131	135	139	142	144	146	150	155	160	170	173	187	205	208	214	220	225	240	261	300
4" Drill							2	2					2			1											2			2		2
BID	2		4	2					5								3		4	2	4	2		3								
Foro 400				2										4					2				2		4						3	
Thermal												1																1				1
Eclipse	1	2			2	3				4	1				3			2								1			4			

Figure 1 - Estimated core quality achieved in past shallow drilling projects, sorted by drill system (rows) and final borehole depth (columns). The scale is from 1 (Excellent) to 5 (Very Poor). Projects that occurred at the Allan Hills are bordered in black.

LESSONS LEARNED FROM DRILLING IN NON-BLUE ICE AREAS

Issues with core quality have been encountered by many drilling groups over the years, even in non-BIAs. Below are various lessons learned about drilling operations and their effects on core quality.

Fine Pitch Drilling: Using fine pitch drilling techniques can improve core quality (Figure 2), although there is a limit as to how fine the pitch can be. Most importantly, drilling at a fine pitch produces finer chips, which are more difficult for the drill to transport away from the cutting head. So much so that, in some cases, attempting to drill at too fine of a pitch can completely halt the drill's ability to penetrate ice.

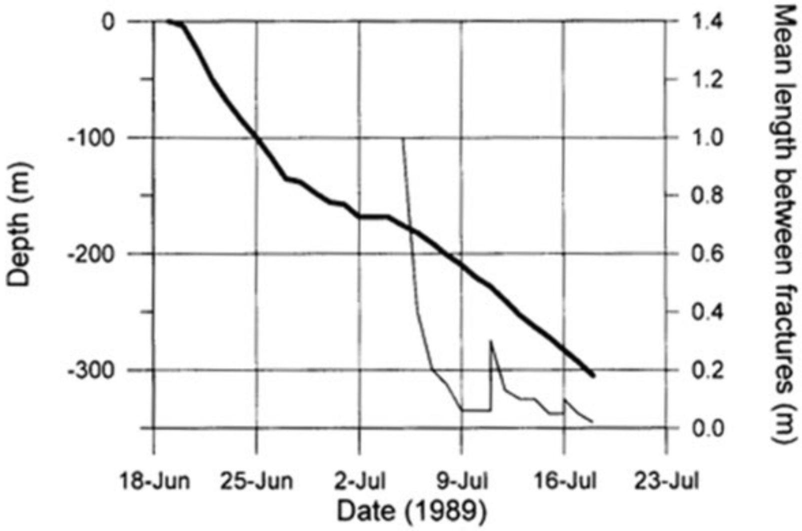


Figure 2: Drilling progress of a 300m core drilled in a dry hole at Summit Station. Note the improvement in core quality on July 11th and 16th when drilling pitch was decresed from 7mm to 3.5mm, and then to 2mm. (Schwander, 1994)

Also, drilling at a finer pitch will increase the time that the drill takes to cut a core. For example, changing from a 7mm pitch to a 2mm pitch adds 1 hour of time per 10 meters drilled. And while 1 hour is not a significant delay, this time can add up when drilling hundreds of meters in a field season.

Step Cutters: While step cutters generally produce a poorer surface finish compared to full kerf cutters, they can aid in chip transport since they produce larger chips. This can allow drilling at a finer pitch in some cases.

Keeping Cutters Sharp: Ensuring that cutters remain sharp is crucial for maintaining core quality and overall drilling performance.

Weight on Top of Core: Installing a weight in the core barrel that rides on top of the core during drilling has been shown to improve core quality with the Eclipse Drill (Morgan, 1998), though results have been mixed with other systems.

Borehole Fluid Column: To reduce the amount of drill fluid that needs to be transported to a field site, drilling groups have experimented with lowering the height of a borehole's fluid column while still maintaining high core quality. IDP has anecdotal evidence of success with this method from drilling a 330-meter core at Summit Station, Greenland in 2024. The fluid column's height was allowed to fall to as little as 80 meters before a reduction in core quality was observed.

The British Antarctic Survey (BAS) examined the effect of low fluid column height on core quality and drill performance in two of their drilling projects. The fluid used for both projects was Exxon Mobil Exxsol D60. They found that:

1. A fluid column height between 100 and 160 meters resulted in good core quality and core production throughout a 364-meter core.
2. No clear correlation between core quality and fluid column height was observed in the data from a 654-meter core (Figure 3). Despite the lack of correlation, it was noted that drilling with a fluid column height of less than 100 meters was difficult, and the core quality was subjectively lower (Triest, 2014).

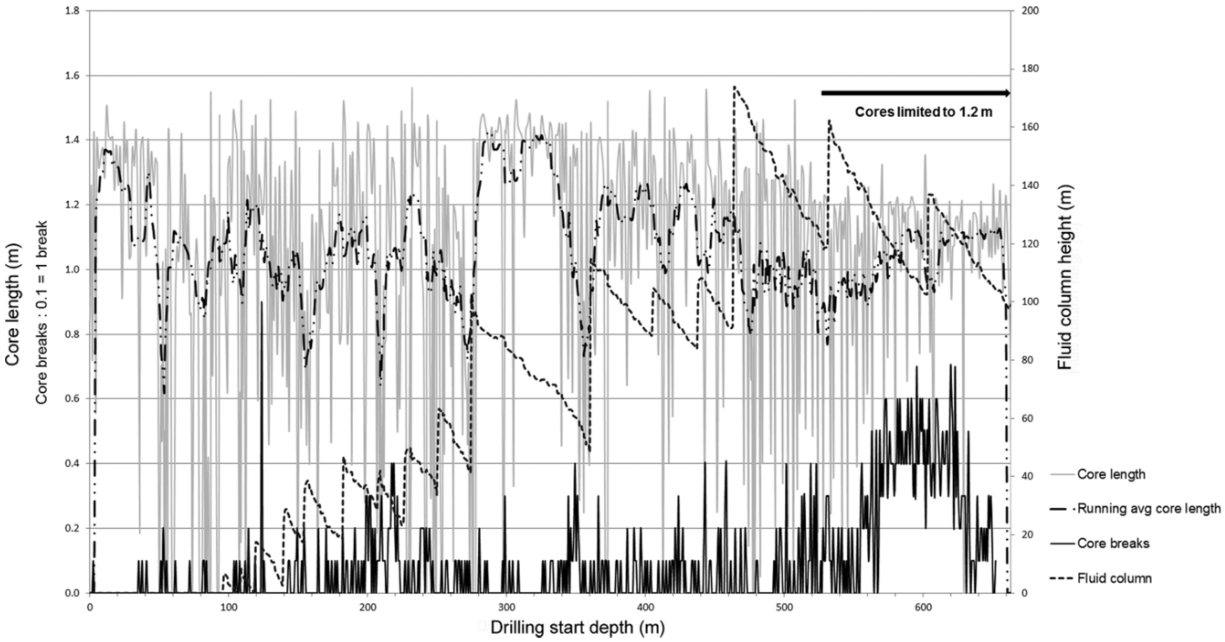


Figure 3: Core and fluid column details from a 654-meter core drilled by BAS (Triest, 2014).

The Danish drilling group from the Center for Ice and Climate, Niels Bohr Institute, conducted a systematic investigation into the effect of fluid column height on core quality while drilling a 303-meter core at Aurora Basin North in Antarctica. The drilling fluid used was Estisol 140. They extrapolated their findings to calculate the required fluid column height to maintain high core quality at greater depths (Figure 4). For a 400-meter core, they recommend a fluid column height of 240 to 290 meters, with an absolute minimum of 180 meters (Sheldon, 2014).

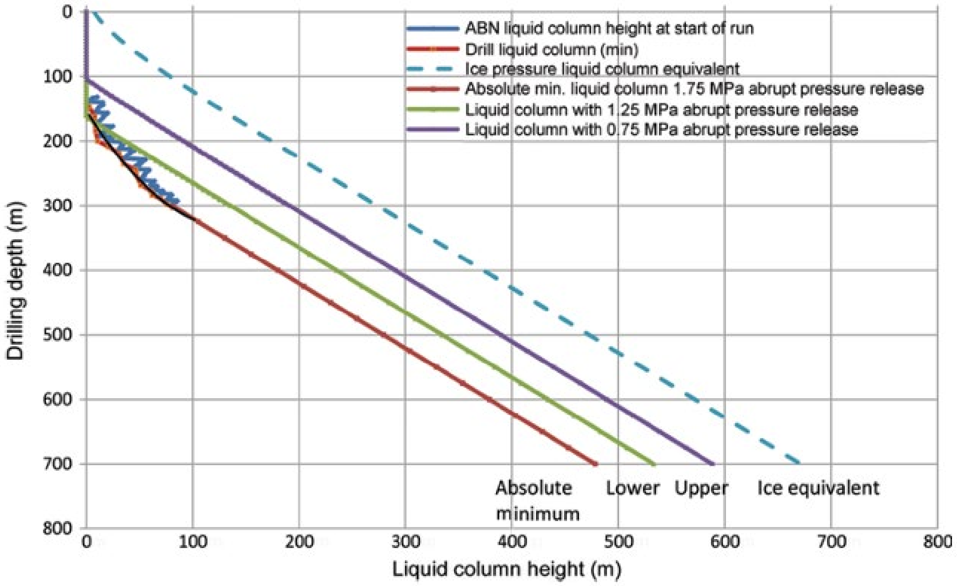


Figure 4: Estimates of fluid column height required to maintain good core quality (Sheldon, 2014).

SCIENCE REQUIREMENTS

Input from the science community was provided on the requirements a solution should meet to be successful. These requirements are listed below.

1. **Electromechanical Drill:** The ice core diameter should be at least 4 inches (101.6 mm).
2. **Thermal Drill:** The ice core diameter should be greater than 9 inches (228.6 mm).
3. **Core Length:** The minimum core length for individual cores is not critical, but the maximum core length is 100 cm.
4. **Development Timeline:** The upgraded or newly developed drill should be developed, tested, and ready for use by the 2025/2026 season at the Allan Hills or Elephant Moraine drill site.
5. **Site Temperature:** The annual mean temperature at the drill site is -30°C.
6. **Current Core Quality Issues:** Cores below approximately 60 meters come up with multiple breaks that make it extremely difficult to log, effectively impossible to subsample ice pieces in a systematic fashion and prevent the possibility of continuous flow analysis. At depths greater than 90 meters, ice frequently comes up in wafers or small pucks, making them unusable for gas analysis.
7. **Desired Core Quality:** Good core quality is defined as ice cores coming up in fewer than four pieces (ideally just one or two) for a 100 cm run and being free of shallow outer fractures formed during the drilling process.
8. **Logistics:** The entire drill system should be transportable in fewer than five Twin Otter flights.

In future discussions of science requirements for drilling in Blue Ice Areas, IDP requests that the following items be addressed:

1. **Core Diameter Requirement for Thermal Drills:** It has been suggested that the 9-inch minimum diameter may not be accurate, and the actual required diameter could be smaller.
2. **Ice Temperature at Drill Sites:** Drilling methods can vary depending on whether the ice is "warm" or "cold," with the general threshold being -10°C.
3. **Unacceptable Drill Fluids:** Clarification on scientific restrictions regarding drill fluids. Are hydrophilic fluids acceptable, knowing that a small amount of the ice core surface will be dissolved?

EVALUATION CRITERIA

Each proposed solution was evaluated on the following criteria:

1. **Core Diameter** – in mm
2. **Cost to develop** –
    a. Short-term solutions – in USD – estimate including equipment, materials, and labor costs.
    b. Long-term solutions – Rated high / medium / low
3. **Time to develop** –
    a. Short-term solutions – prediction for which Antarctic season the system could be ready for issue (25/26, 26/27, or 27/28).
    b. Long-term solutions – Rated long / medium / short – the time from science community approval, NSF approval, and IDP's receipt of funding to the system being ready for issue, including time for R&D.
4. **Logistics Load** –
    a. Short-term solutions – in number of Twin Otter flights – using an ACL of 2500 lb.[1] and a cargo area of 126 cu. ft.[2]. This estimate includes drill cargo and drilling fluid but does not include generators or fuel. A 100m fluid column and 30% loss is used to estimate drill fluid volume.
    b. Long-term solutions – Rated high / medium / low
5. **Confidence in Attaining Good Core Quality** – Scored 1 to 5

    1 – No confidence – Would expect same results as current drilling method (dry electromechanical drilling)

    2 – Low confidence – In theory, results should be improved, but method has not been used in the field

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[1] 2500 lb. ACL (Allowable Cabin Load) advised by Matthew Kippenhan (Antarctic Support Contract) for a 280 nm trip with refuel available at the destination or a 120 nm trip without refuel available.

[2] 126 cu. ft. cargo area taken from the USAP Continental Field Manual.

    3 – Moderate confidence – Aspects of the method have been field-proven, but significant unknowns remain
    4 – High confidence, drilling method is field-proven in non-Blue Ice Areas
    5 – Full confidence, drilling method is field-proven in Blue Ice Areas

6. **Field season length for 400m core –**
    a. Short-term solutions – in days – including set-up, drilling, fluid bailing, and take-down for two drillers working a 10-hour shift. Does not include days off.[3]
    b. Long-term solutions – Rated long / medium / short

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[3] Assumes 2 days for set up, 1 day for fluid bailing, and 2 days for take down for each solution.

SHORT-TERM SOLUTIONS

Throughout the year that this feasibility study was conducted, a more urgent need for improved core quality at Allan Hills was realized by the COLDEX team. Since wet drilling is a well-recognized solution to improving core quality, IDP was asked to evaluate options to implement wet drilling at the Allan Hills in the earliest field season possible. The evaluation of those options is summarized here.

SOLUTION 1 – ADAPT FORO 400 FOR WET DRILLING

Currently, Foro 400 can retrieve 1m long, 98mm diameter ice cores from a dry borehole down to a depth of 400m. Adapting the Foro 400 Drill to have wet drilling capabilities would entail:

1. Designing and building 1m versions of the Foro1650 barrel set to be used with the existing anti-torque and motor sections.
2. Designing and building a core processing line for drill lay down and core removal.
3. Making modifications to the winch and tower assemblies to include drip trays and features to aid in laying down the drill.
4. Purchasing fluid handling equipment such as a vacuum, fluid bailer, chip melter, fluid cooler, drum pump, hollow shaft heater, drip trays, etc.

Criteria	Value	Justification
Core Diameter	98 mm	Can reuse Foro barrel designs and cutter hardware
Cost to Develop	$382,000	IDP budgetary estimate
Time to Develop	RFI by 25/26	Existing designs to use as starting points; have long lead materials in hand
Logistics Load	2.7 Twin Otter flights	Drill cargo: 4070 lbs., 266 cube Drill fluid: 8 drums
Confidence in Attaining Good Core Quality	4 – High	The Foro1650 barrel design is field proven to produce excellent quality core. (Souney, 2021)
Field Season Length for 400m Core	40 days	20m/day dry drilling, depths 0-100m[4] 10m/day wet drilling, depths 100-400m

Table 2: Evaluation of short-term solution 1 – Adapt Foro 400 for wet drilling.

SOLUTION 2 – PURCHASE A WET DRILLING VERSION OF AN ECLIPSE DRILL

The Eclipse Drill is an off-the-shelf ice coring drill produced by Icefield Instruments. There are two versions available for purchase: one producing an 81mm diameter core and one producing a

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[4] A core production rate of 20 meters per day was achieved with Foro 400 at Summit in 2024

102mm diameter core. The drill is typically operated in a dry borehole, however there are add-ons available to allow drilling with fluid. IDP has two of these drills in inventory; both produce 81mm diameter core and neither have the fluid drilling add-ons.

In 2023, IDP received a quote from Icefield Instruments for a 102mm Eclipse Drill with wet drilling capabilities. The quote included the main components of the drill system (winch, level-wind, tilting-tower, sonde, control panel), but did not include equipment necessary for fluid handling. Further, IDP has upgraded certain components of the Eclipse Drills in inventory to improve function and durability and would plan to make the same improvements to this new system.

Criteria	Value	Justification
Core Diameter	102 mm	Larger diameter option best meets the science requirements
Cost to Develop	$425,000	IDP budgetary estimate
Time to Develop	RFI by 25/26	Quoted lead time is 5 months[5]
Logistics Load	2.4 Twin Otter flights	Drill cargo: 2600 lbs., 180 cube Drill fluid: 10 drums
Confidence in Attaining Good Core Quality	3 to 4 – Moderate to High	Successes seen in the field by Icefield Instruments[6]
Field Season Length for 400m Core	38 days	35 m/day dry drilling, depths 0-100m 10m/day wet drilling, depths 100-400m

Table 3: Evaluation of short-term solution 2 – Purchase a wet drilling version of an Eclipse Drill.

SOLUTION 3 – REDESIGN THE BLUE ICE DRILL TO BE WET DRILLING CAPABLE

The Blue Ice Drill (BID) was originally designed to retrieve 241mm diameter cores from a maximum depth of 30m. The drill was subsequently modified to allow deeper coring to 200m depth. Adapting the current BID to have wet drilling capabilities would entail:

1. Designing and building wet versions of the core barrel sets.
2. Modifying the motor sections to be sealed so that they can operate in a fluid-filled borehole. This could require redesigning the motor sections.
3. Designing and building a core processing line for drill lay down and core removal.
4. Making modifications to the winch and tower assemblies to include drip trays and features to aid in laying down the drill.
5. Purchasing fluid handling equipment such as a vacuum, fluid bailer, chip melter, fluid cooler, drum pump, hollow shaft heater, drip trays, etc.

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[5] The drill quoted in 2023 has since been sold and is no longer available for purchase.

[6] As presented by Icefield Instruments at the 8th International Ice Drill Symposium (2019)

Note that these modifications are the minimum that would be required to allow the BID to drill in a fluid-filled borehole. The estimates do not include the cost or time required to revamp the system as a whole or to improve the core quality produced while dry drilling.

Criteria	Value	Justification
Core Diameter	241 mm	Reuse existing cutter head hardware
Cost to Develop	$500,000	Rough estimate based on the Foro 400 adaptation cost. A BID adaptation would require additional labor and materials.
Time to Develop	RFI by 27/28	No existing designs for barrel sets or sealed motor sections.
Logistics Load	8.2 Twin Otter flights	Drill cargo: 6250 lbs., 405 cube Drill fluid: 41 drums
Confidence in Attaining Good Core Quality	3 – Moderate	Wet drilling should significantly improve core quality, but IDP has no wet drilling experience with this large of a core diameter.
Field Season Length for 400m Core	N/A	The max depth of the BID is 200m.

Table 4: Evaluation of short-term solution 3 – Redesign the Blue Ice Drill to be wet drilling capable.

SOLUTION 4 – FORO-SIZED SONDE ON THE 700 DRILL

The 700 Drill can produce 70mm diameter ice cores in a fluid-filled borehole down to depths of 700m. As a 70mm diameter core is too small for the analysis being done by COLDEX at the Allan Hills, the option to use a Foro-sized (98mm core) sonde with the 700 Drill's surface equipment was suggested. Adapting the 700 Drill to produce a 98mm diameter core would entail:

1. Updating the Foro1650 motor section electronics to be compatible with the 700 Drill control system.
2. Designing and building 1-meter versions of the Foro1650 barrel set to be used with the updated Foro1650 motor sections.
3. Making minor modifications to the 700 Drill core processing line to be compatible with 98mm diameter cores.

Criteria	Value	Justification
Core Diameter	98 mm	Can reuse Foro barrel designs and cutter hardware
Cost to Develop	$289,000	IDP budgetary estimate
Time to Develop	RFI by 25/26	Existing designs to use as starting points; have long lead materials in hand
Logistics Load	3.3 Twin Otter flights	Drill cargo: 5135 lbs., 360 cube Drill fluid: 8 drums
Confidence in Attaining Good Core Quality	4 – High	The Foro1650 barrel design is field proven to produce excellent quality core. (Souney, 2021)
Field Season Length for 400m Core	29 days	30m/day dry drilling, depths 0-100m 15m/day wet drilling, depths 100-400m[7]

Table 5: Evaluation of short-term solution 4 – Foro-sized sonde on the 700 Drill.

COMPARISON & RECOMMENDATION

The evaluations of proposed short-term solutions are summarized in Table 6 below.

ID	Solution	Core Diameter	Cost to Develop	Ready for Issue	Number of Twin Otter Flights	Confidence in Method [1-5]	Field Season Length for 400m Core
1	**Wet Foro 400**	98 mm	$382,000	25/26	2.7	4	40 days
2	**Wet Eclipse**	102 mm	$425,000	25/26	2.4	3-4	38 days
3	**Wet BID**	241 mm	$500,000	27/28	8.2	3	N/A
4	**Foro Sonde on 700 Drill**	98 mm	$289,000	25/26	3.3	4	29 days

Table 6: Summary of the evaluations of each short-term solution. Green cells indicate a particularly good evaluation, while red cells indicate a less desirable evaluation.

NSF, IDP and the scientific community have selected to pursue Solution #4 – Building a Foro-sized sonde for use with the 700 Drill. The plan is to use this system at the Allan Hills in the 25/26 Antarctic season.

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[7] Core production rates of 30 meters/day (dry) and 15 meters/day (wet) were achieved with the 700 Drill at Summit in 2024.

LONG-TERM SOLUTIONS

The selected short-term solution is a combination of parts from multiple IDP drill systems. While it is being used in the field, the 700 Drill, Foro 400 Drill, and Foro 1650 Drill will be unavailable for use on other projects.

If in the future the scientific community desires to have a drill dedicated to retrieving high quality ice cores from depths down to 400 meters in BIAs, the following solutions are presented and compared for NSF and scientific community consideration.

SOLUTION 5 – ELECTROMECHANICAL DRILL FOR SHALLOW FLUID-FILLED BOREHOLES

Using an electromechanical drill in a fluid-filled borehole is the obvious first choice to improve core quality. This is the method used by most, if not all, deep-coring projects in Antarctica and Greenland. IDP has direct experience with this method of drilling from three coring projects:

- The South Pole Ice Core (SPICEcore) project used the Foro1650 Drill to core to a depth of 1751 meters from 2014 to 2016.
- The West Antarctic Ice Sheet (WAIS) Divide ice core project used the Deep Ice Sheet Coring (DISC) Drill to core to a depth of 3405 meters from 2007-2012.
- The 700 Drill was used to core to a depth of 330 meters at Summit Station in 2024.

The Foro1650 Drill and the 700 Drill are both Hans Tausen (HT) style drills which produced high quality ice cores for these projects. The DISC Drill is not a HT style drill, and it appears that the core quality was not as good compared to Foro1650 at the same depths (Figure 5). It should be noted that it is unknown whether this difference in core quality was due to the drill’s style, the ice characteristics at each site, or some other factor.

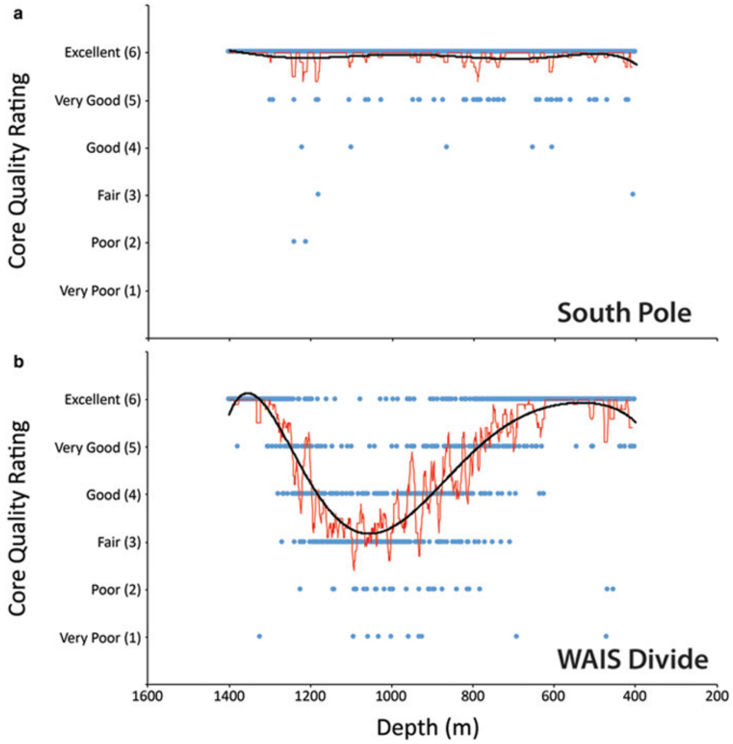

Figure 5: Ice core quality vs depth in (a) the SPICEcore using Foro1650 and (b) the WAIS Divide ice core using DISC. (Souney, 2021)

The new drill system would be very similar to the 700 Drill in that it would be a logistically minimal Hans-Tausen style coring drill for use in fluid-filled boreholes. The differences would be the core diameter (input required from science community) and winch depth capacity (400 meters instead of 700 meters).

CORE DIAMETER – TO BE SPECIFIED BY SCIENCE COMMUNITY

The core diameter for this drill system could be selected by the science community to fit the needs of the analysis methods. For reference, IDP has experience drilling cores as large as 241mm in diameter. The main restriction on core diameter is the amount of drilling fluid needed. For more details on drilling fluid volume, see Logistics Load below.

COST TO DEVELOP – HIGH

This system would be built completely new from the ground up and would likely have a similar final cost to the 700 Drill.

TIME TO DEVELOP - MEDIUM

The time to develop this system would be similar to the time taken to develop the 700 Drill. However, lessons learned from the 700 Drill would likely speed up the process and the amount of R&D required would be minimal.

LOGISTICS LOAD – HIGH

This solution will have a high logistics load due to the transportation of drill fluid. It's reasonable to assume that any of the proposed solutions will require 1 or 2 Twin Otter flights to transport the drill cargo, while the number of additional flights required is dependent on the amount of drill fluid needed to fill the borehole. Table 7 lists the number of Twin Otter flights needed to transport drill fluid for various core and borehole diameters.

Note that the logistics load for this solution is highly dependent on core diameter and can quickly surpass the science requirement of fewer than 5 Twin Otter flights.

Core Diameter	Corresponding IDP Drill System	Fluid Column Height	Number of 55 Gallon Drums	Number of Twin Otter Flights
70 mm (98mm borehole)	700 Drill	100 m	5	0.7
		400 m	19	2.6
98 mm (126mm borehole)	Foro Series	100 m	8	1.1
		400 m	32	4.4
150 mm (178mm borehole)	None	100 m	16	2.2
		400 m	63	8.7
241 mm (288mm borehole)	BID	100 m	41	5.7
		400 m	163	22.8

Table 7 - Amount of drill fluid required for various core/borehole diameters. Values are given for 100m and 400m fluid columns. Note that these values are for comparison use only and should not be used for specific season planning.

CONFIDENCE IN ATTAINING GOOD CORE QUALITY – 4 OUT OF 5 – HIGH

This method of drilling is field proven by IDP and several other drilling groups to produce high quality ice cores. The caveat in Blue Ice Areas is that the ice seems to be considerably more stressed, potentially behaving like brittle ice, so there is still some uncertainty.

FIELD SEASON LENGTH FOR A 400M CORE – SHORT

Electromechanical drilling is generally fast and able to achieve a 15m/day production rate, especially if the winch is sized appropriately to trip through drill fluid.

SOLUTION 6 – ELECTROTHERMAL DRILL FOR COLD ICE

Electrothermal drills were widely used up to and through the 1980s but were eventually phased out in favor of electromechanical drills, which are faster and more energy efficient. Despite this shift, past IDP thermal drill projects have consistently produced excellent core quality, even at depths reaching 300 meters (Figure 1). However, IDP's current thermal drill is only suitable for use in warm ice (>-10°C) as there is no method to remove the meltwater from the borehole. In ice colder than -10°C, the meltwater will refreeze too quickly between coring runs. To adapt this technology for cold ice, a new drill would need to be designed to manage meltwater, either through removal from the borehole or dilution with a hydrophilic drill fluid (ethanol is commonly used for this purpose).

The thermal stresses on an ice core during drilling can negatively impact core quality, but the use of a drill fluid in the borehole has been shown to mitigate some of these effects. Ensuring fluid flow at the drill head can further help in reducing thermal stress and potentially improve the overall core quality. For this reason, a thermal drill that dilutes the meltwater rather than removes it is preferred for the purpose of this study and will be the focus for evaluation. IDP also suspects that having a fluid-filled borehole will improve core quality due to the increased pressure on the core, much the same as in electromechanical drilling.

A major disadvantage of thermal drills is that they struggle to penetrate through rocks, sediment, or grit, making their use at certain Blue Ice Areas (i.e. the Allan Hills) problematic. It may be possible to provide a separate downhole tool to act as a rock buster, or to provide a debris vacuum similar to what IDP uses with the current thermal drill. But the inability to drill through dirty ice will slow drilling progress even further compared to an electromechanical drill.

CORE DIAMETER – TO BE SPECIFIED BY SCIENCE COMMUNITY

For reference, IDP’s current electrothermal drill produces an 86mm core and the largest core produced by a thermal drill is 195mm (Australian Antarctic Expedition drill, a version of the CRREL Mk II drill).

Please also note that thermal drilled cores may not be acceptable for certain scientific analyses and may require the drill to produce an oversized core to obtain enough usable volume.

COST TO DEVELOP – HIGH

This system would be built completely new from the ground up and likely would have a greater final cost than the 700 Drill. For a thermal drill add-on to an existing IDP drill system, see Solution 7a.

TIME TO DEVELOP – LONG

IDP does not have direct experience with cold-ice thermal drills. As such, more time for R&D would be required compared to electromechanical drill solutions.

LOGISTICS LOAD – MEDIUM

The amount of drill fluid required to maintain core quality while thermal drilling is not well understood. It is possible that a thermal drill requires the same amount of drill fluid as an electromechanical drill. However, one potential logistics saving that this solution provides is the ability to use an antifreeze-water solution as the drill fluid.

The effect that this has on logistics is that only 30%-50% of the drill fluid needs to be transported to the drill site to attain the same fluid column height as an electromechanical drill using a hydrophobic fluid (i.e. Estisol 140, Isopar K). The water component of the solution is made up of meltwater from the borehole and any additional water can be melted at the drill site.

A factor that has yet to be considered is how to dispose of the antifreeze solution at the end of the project. If left in the hole, the solution will further dilute until it freezes, which may not be acceptable from an environmental standpoint. If removed from the hole, the fluid will need to be transported away from the drill site, which will increase the logistics load significantly as the volume has increased by a factor of 2 to 3 with the addition of water. There are methods to separate the water from the solution, but it is unknown if any of those are viable for a field camp.

CONFIDENCE IN ATTAINING GOOD CORE QUALITY – 3 OUT OF 5 – MODERATE

Since the ice drilling community has largely moved away from thermal drills in recent history, there is little information available on their performance regarding core quality. But one publication (Zagorodnov, 2014) suggests that good quality ice core can be attained with this drilling method. Also, IDP has had great success achieving excellent core quality with our Thermal Drill, however those successes have been at sites very different from Blue Ice Areas.

One aspect to note is that using a hydrophilic fluid in the borehole will “melt” the borehole walls and the surface of the ice cores. Publications suggest that this is minimal, but it would need to be studied further to determine if scientific goals are affected.

FIELD SEASON LENGTH FOR A 400M CORE – LONG

Existing electrothermal drills have penetration rates in the range of 1 to 5 m/h. Compared to rates attained with electromechanical drilling (5 to 20 m/h), thermal drills are slow and will require a longer season to reach the same depth. Also, thermal drills are greatly affected by debris-laden ice and will slow even further in areas with dirty ice.

SOLUTION 7A – DRILL SYSTEM WITH SWAPPABLE SONDES (RETROFIT SYSTEM)

This solution involves a drill system with interchangeable sondes, allowing for flexibility in drilling method. The system would be capable of switching between electromechanical and electrothermal drilling, depending on the ice conditions and project requirements. In a Blue Ice Area, the general idea would be to start the borehole with the mechanical sonde, then switch to the thermal sonde when core quality deteriorates. This allows the project to get the benefit of high production rates from the mechanical sonde in the upper portion of the borehole, while still attaining good core quality at deeper depths with the thermal sonde. However, the uncertainties around core quality in thermal drills described in Solution 6 still apply.

IDP already has several drill systems with mechanical sondes. A feasibility study was done to determine if it is realistic to add a thermal sonde to the 700 Drill, the Foro 400 Drill, or the Blue Ice Drill. The study’s focus was on the amount of power that can be delivered to the sonde, the resulting penetration rate, and what surface components would need to be rebuilt. The results in

Table 8 show that this solution is feasible, however the penetration rate would be much slower than electromechanical drilling.

Drill System	Power Available at Sonde	Thermal Sonde Penetration Rate (estimated)	Mechanical Sonde Penetration Rate (for reference)	New Surface Equipment Required
700 Drill	1084 W	1.60 m/h	~5 to 20 m/h	None
Foro 400 Drill	1777 W	2.00 m/h	~5 to 20 m/h	New control box
Blue Ice Drill	2400 W	1.17 m/h	~5 to 20 m/h	New control box

Table 8: Estimated penetration rates that could be achieved by a thermal sonde used on 3 existing IDP drill systems.

CORE DIAMETER – 70MM, 98MM, OR 241MM

These are the core sizes of the 700 Drill, Foro 400 Drill, and Blue Ice Drill, respectively.

COST TO DEVELOP – MEDIUM

As this solution does not entail building an entirely new system, costs will be somewhat reduced.

TIME TO DEVELOP – MEDIUM

As this solution does not entail building an entirely new system, the time to develop would be reduced. Some R&D would be required in the design of the cold-ice thermal sonde.

LOGISTICS LOAD – MEDIUM

Repeat of Solution 6.

CONFIDENCE IN ATTAINING GOOD CORE QUALITY – 3 OUT OF 5 – MODERATE

Repeat of Solution 6.

FIELD SEASON LENGTH FOR 400M – MEDIUM

Mechanical drilling is relatively fast, while thermal drilling is slow. Using a combination of these methods, the field season length would be between Solutions 5 and 6.

SOLUTION 7B – DRILL SYSTEM WITH SWAPPABLE SONDES (NEW SYSTEM)

This solution is the same as Solution 7a, except that an entirely new system would be built instead of retrofitting an existing system to include a thermal sonde. The benefits of this include:

1. Flexibility in selecting core diameter
2. Increased penetration rates for the thermal sonde

CORE DIAMETER – UNSPECIFIED

For reference, IDP’s current electrothermal drill produces an 86mm core and the largest core produced by a thermal drill is 195mm (Australian Antarctic Expedition drill, a version of the CRREL Mk II drill).

Please also note that thermal drilled cores may not be acceptable for certain scientific analyses and may require the drill to produce an oversized core to obtain enough usable volume.

COST TO DEVELOP – HIGH

This system would be built completely new from the ground up and likely would have a greater final cost than the 700 Drill.

TIME TO DEVELOP – LONG

IDP does not have direct experience with cold-ice thermal drills. As such, more time for R&D would be required compared to electromechanical drill solutions.

LOGISTICS LOAD – MEDIUM

Repeat of Solution 6.

CONFIDENCE IN ATTAINING GOOD CORE QUALITY – 3 OUT OF 5 – MODERATE

Repeat of Solution 6.

FIELD SEASON LENGTH FOR 400M – MEDIUM

Repeat of Solution 7a, except slightly increased thermal drill penetration rates could be expected as the system is designed for that purpose.

SOLUTION 8A – IMPROVED ELECTROMECHANICAL DRILL FOR DRY BOREHOLES (RETROFIT SYSTEM)

This solution would entail making modifications to the Foro 400 Drill or the Blue Ice Drill to improve their core quality in dry boreholes. The exact modifications that would be made are not yet decided, but may include some or all of the following suggestions:

Spinning Outer Barrel or Triple-Tube Core Barrel:

Most electromechanical drills use a two-barrel design where the inner barrel rotates while the outer barrel remains stationary. This can negatively affect core quality if chips build up on the outside of the core and interfere with the inner barrel rotating around the stationary core. Modifying the barrel set so that the outer barrel rotates, and the inner barrel remains stationary could mitigate this effect.

Similarly, the rock drilling industry commonly uses a triple-tube core barrel where the inner and outer barrels are stationary while the intermediate tube rotates. Adapting this style of core barrel for ice drilling could improve core quality.

Fine Pitch Drilling:

As described in the Lessons Learned section of this report's Introduction, drilling with a very low pitch has been shown to improve core quality, up until the chips become too fine to transport well. An interesting idea proposed in literature involves using a "pre-cutter" that uses a very fine pitch at the core's outer diameter but then uses normal cutters for the rest of the kerf area that still produce large enough chips to transport easily (Figure 6).

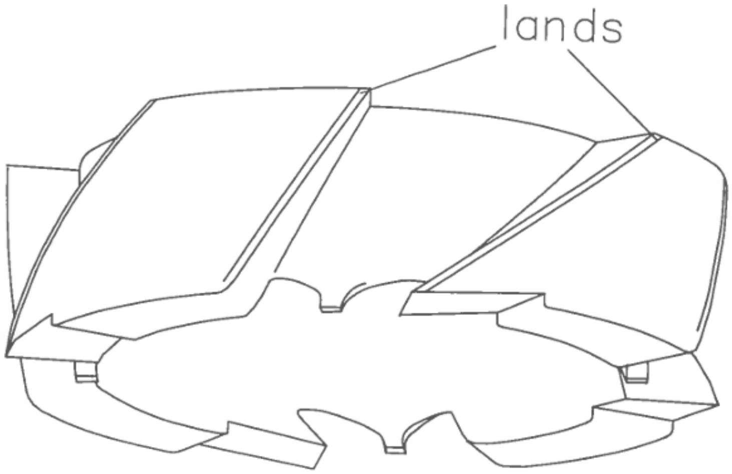

Figure 6: Drill head with pre-cutters (Schwander, 1988)

Another option is to redesign the cutter head to be more similar to a hole saw, which uses many teeth around the annulus instead of just three. This would reduce the mechanical stress seen by the core as it is cut out of the ice sheet. Again, a new method for chip transport would be required to handle the very fine chips that are created.

Air Circulation for Chip Transport

An idea presented in literature is to use forced air circulation to transport chips. In this case, the forced air would replace the role of drill fluid in a typical wet drill. The benefit would be that the drill could use a high-speed cutting tool and produce extremely fine chips that would be removed by the air stream. This method of dry drilling is unproven but shows promise (Hu, 2019).

CORE DIAMETER – 98MM OR 241MM

Modifications could be made to either the Foro 400 Drill or the Blue Ice Drill.

COST TO DEVELOP – LOW

Costs would be limited to the design and fabrication of the sonde modifications. Minimal modifications would be needed for the surface equipment.

TIME TO DEVELOP – MEDIUM

Some R&D would be required for the sonde design, but the development would be relatively quick as minimal changes would be needed to surface equipment.

LOGISTICS LOAD – LOW

The logistics load for this solution would be low as no drill fluid would need to be transported.

CONFIDENCE IN ATTAINING GOOD CORE QUALITY – 2 OUT OF 5 – LOW

Dry drilling methods such as these are not field proven.

FIELD SEASON LENGTH FOR 400M – SHORT

Assuming an improved dry drill will maintain the penetration speeds of other electromechanical drills, the field season would be short compared to other methods of drilling.

SOLUTION 8B – IMPROVED ELECTROMECHANICAL DRILL FOR DRY BOREHOLES (NEW SYSTEM)

This solution is the same as 8a, except that an entirely new system would be developed instead of modifying an existing system.

CORE DIAMETER – UNSPECIFIED

The core diameter for this drill system could be selected by the science community to fit the needs of the analysis methods. For reference, IDP has experience drilling cores as large as 241mm in diameter.

COST TO DEVELOP – HIGH

This system would be built completely new from the ground up and likely would have a greater final cost than the 700 Drill.

TIME TO DEVELOP – LONG

The time to develop this system would be greater than the time taken to develop the 700 Drill due to the R&D that would be required for the sonde’s design.

LOGISTICS LOAD – LOW

Repeat of Solution 8a.

CONFIDENCE IN ATTAINING GOOD CORE QUALITY – 2 OUT OF 5 – LOW

Repeat of Solution 8a.

FIELD SEASON LENGTH FOR 400M – SHORT

Repeat of Solution 8a.

COMPARISON AND RECOMMENDATION

The evaluation's results are presented in Table 9. Currently, IDP is not recommending a specific long-term solution. Each of the options has merits and further discussion between IDP, NSF, the science community, and the logistics provider is recommended to select a solution supported by all parties.

ID	Solution	Core Diameter	Cost to Develop	Time to Develop	Logistics Load	Confidence in Method [1 to 5]	Field Season Length for 400m core
5	**New Wet Drill**	Unspecified	High	Medium	High	4 – High	Short
6	**New Thermal Drill**	Unspecified	High	Long	Medium	3 – Moderate	Long
7a	**Swappable Sondes – Retrofit**	70, 98, or 241mm	Medium	Medium	Medium	3 – Moderate	Medium
7b	**Swappable Sondes – New**	Unspecified	High	Long	Medium	3 – Moderate	Medium
8a	**Improved Dry Drill**	98 or 241mm	Low	Medium	Low	2 – Low	Short
8b	**New Dry Drill**	Unspecified	High	Long	Low	2 – Low	Short

Table 9: Summary of the evaluations of each long-term solution. Green cells indicate a particularly good evaluation, while red cells indicate a less desirable evaluation.

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LIST OF ACRONYMS

ACL	Allowable Cabin Load
BAS	British Antarctic Survey
BIA(s)	Blue Ice Area(s)
BID	Blue Ice Drill
DISC	Deep Ice Sheet Coring (Drill)
HT	Hans Tausen
IDP	NSF Ice Drilling Program
NSF	National Science Foundation

R&D	Research and Development
RFI	Ready for Issue
SPICEcore	South Pole Ice Core
USAP	United States Antarctic Program
USD	United States Dollar
WAIS	West Antarctic Ice Sheet