# Intermediate Depth Drill Development: Summary Document April 2012

Ice Drilling Program Office /

Ice Drilling Design and Operations group

(IDPO / IDDO)

# Intermediate Depth Drill Development

## Background

*The need for an intermediate drill* - Existing quantitative reconstructions of the past two millennia are not yet definitive, in part due to a lack of annual data prior to 1600 AD in many areas, and to the highly regional nature of many climate processes. The search for evidence of climate history over the last several thousand years requires an ice coring drill that can penetrate up to 1,500m of ice. In addition, the need to better understand ice dynamics processes for improved predictions of current ice sheet behavior in response to warming conditions requires a drill that can penetrate similar depths. Climate and environmental science issues relating to the past 500-1000 years require cores from depths of 400 m or more. The need to access areas with limited available logistics requires that the drill be portable and versatile for use under a variety of conditions. The U.S. ice drilling program has agile drills capable of drilling to approximately 300 m, and a deep ice drill capable of drilling to approximately 4000 m, but does not have a drill that meets the need for portable intermediate depth drilling over depths of 400-1,500 m. The need for an intermediate drill, voiced by the many in the research community and deemed high priority by the Science Advisory Board of the Ice Drilling Program Office (IDPO), led to articulation of the goal of acquiring a versatile intermediate-depth (300 - 1500 m) ice coring drill in the IDPO Long Range Science Plan and the corresponding Ice Drilling Design and Operations (IDDO) Long Range Drilling Technology Plan. The purpose of this document is to outline the multi-year plan of action for IDPO/IDDO acquisition of an intermediate depth drill.

*International collaboration* - An ice coring drill currently in use in the Danish ice coring program at the Centre for Ice and Climate (CIC) is the Hans Tausen drill (Johnsen et al, 2007), which has many of the desired attributes of an intermediate depth drill, except that in its current design it is practical for shallower depths than identified for the Intermediate Depth Drill. The EPICA drill is an adaptation of the Hans Tausen drill for very deep cores. Both IDPO and IDDO have significant interactions with CIC, which help to set the stage for productive collaborations. The lead of CIC, Dorthe Dahl-Jensen, is a member of the IDPO Science Advisory Board, and Steffen Bo Hansen, the lead drilling engineer from CIC, is a member of the IDDO Technical Advisory Board. CIC personnel had expressed willingness to assist IDPO/IDDO with development of an intermediate drill for a number of reasons including improvements to some aspects of the Hans Tausen drill, and the production of another drill sonde for themselves and an identical one for the US program. Ice drilling entities in other nations (NZ and Germany) have been developing intermediate drills based on modification of the Hans Tausen design.

Following invitation from the Leader of the Centre for Ice and Climate for an engineer from the U.S. to participate in the summer 2010 testing of a NZ prototype intermediate drill at the NEEM site in Greenland, IDPO worked with the NSF and its logistics contractor, CH2MHill Polar Services, to get approval to send IDDO engineer Tanner Kuhl from IDDO to observe the 2010 drill test. This gave Kuhl an excellent opportunity to discuss the drill with engineers and drillers from both Denmark and New Zealand, and to create recommendations on a path forward for IDPO/IDDO. In February 2011, two IDDO staff members visited the CIC to further review the

Hans Tausen drill and discuss possible design modifications. In 2011, IDPO led discussions between personnel from IDPO/IDDO and CIC, and then with NSF, to determine the nature of the international collaboration. During the summer of 2011, IDDO engineer jay Johnson had the opportunity to observe drilling at NEEM with the Danish deep drill, which is based on the Hans Tausen Drill; this allowed IDDO personnel to become even more familiar with the drill concept develop by CIC. Table 1 identifies strengths and weaknesses of various approaches for international partnering. As shown in Table 1, collaboration based on exchange of information with the CIC was the obvious choice. It reduces cost and schedule risks by leveraging on the CIC recent design and fabrication experience, without committing budget or equipment or possible schedule delays to an international entity. IDPO recommended to the NSF that the most expedient way forward for acquiring an intermediate depth drill for the U.S. ice drilling program would be through collaboration with the CIC based on exchange of information and pooled expertise. IDPO received approval from NSF for the collaboration including NSF legal approval of the wording of the letter of collaboration. The letter of collaboration from the CIC is attached in Appendix A.1, and the IDPO letter of collaboration as approved by NSF is attached in Appendix A.2.

Table 1. Considerations for international partnering for the Intermediate Depth Drill

| **Option** | **Strengths** | **Weaknesses** |
|---|---|---|
| Stand- alone IDDO design and production | Allows innovation in the design to meet US ice drilling requirements independently | Longer development time and higher development costs because it is not based on a proven design (i.e., the HT drill) |
| Collaboration with CIC based on coordinated production, with the CIC producing two sondes and IDDO providing two sets of anti-torques etc | -Economies of scale<br>-Good will from joint build<br>-Move toward a common international design for an IDD | -Lack of justification to provide equipment parts for foreign entity<br>-Risk of different time constraints between CIC and IDDO<br>-Likely delays due to need for NSF approval of complex international collaboration |
| Collaboration based on exchange of information only | -Reduces risk through use of existing component design while allowing some improvements to design<br>-Minimizes risk of delays and loss of control with product scope and construction<br>-Good will from two-way information generation and flow<br>-All components of the drill and acquisition/creation of spares are controlled by IDDO<br>- Resulting complete design available to international community for common drill | -Risk of incomplete or out of date designs from CIC<br>-Higher cost of IDDO design and construction of all parts than if CIC designed and built sondes |

*Science requirements of the drill* – IDPO formulated draft science requirements based on information in the Long Range Science and Technology Plan, circulated it among the community and IDDO for input, and formulated the final science requirements. For development projects, IDPO identifies a Lead Scientist from the community who is interested in working closely with IDDO on quick interactions regarding finer details of the design. For the Intermediate Depth Drill, Drs. Eric Saltzman and Eric Steig are Co-Lead Scientists, since they will likely be the first users of the drill. The Science Requirements for the Intermediate Depth Drill, which were approved both by IDPO and by scientists Eric Saltzman and Eric Steig, are given in Appendix B.

## Intermediate Depth Drill Development Plan

***Scope & Deliverables***

The IDPO will work with the research community, IDDO, and NSF to plan development of the intermediate depth drill, and IDPO will oversee the development and testing of the Intermediate Depth Drill by IDDO. The development of the drill will be carried out by IDDO, with technical information for parts of the drill supplied by CIC and elsewhere. Development of the drill includes conceptual design, technical engineering design and construction, a field test of the drill, and possible modifications pending the outcome of the field test. The deliverable is a working drill that meets the IDPO Science Requirements.

***Schedule & Responsibilities***

Milestones in the development are listed in Table 2 below. Responsibilities of IDPO are to work with the research community, NSF, and IDDO to identify science requirements and plan drill development in a way that will produce ice cores to the quality needed by the science within the time frame identified, in compliance with the logistical goals of the drill, and within the budget identified for drill development. IDPO is responsible for oversight of IDDO in drill development, including reviewing progress against approved schedule and budgets using, among other tools, EV measures; controlling changes in scope, schedule and budget; and facilitating communication between IDDO and the science community. Co-Lead scientists who will be first users of the drill, Drs. Eric Steig and Eric Saltzman, may interact with IDDO for quick answers to minor questions. They will also provide feedback and advice, including possible recommendations of changes to the Science Requirements, to IDPO. If Saltzman and Steig recommend changes in the Science Requirements, IDPO will work with the community to ensure that proposed changes in the science requirements are consistent with the community vision for the drill, will seek approval for updating the Science Requirements, and will work with IDDO to modify the project budget and schedule as necessary in response to the change in project scope. IDPO/IDDO will report financial status and progress on Intermediate Drill Development to NSF on monthly, quarterly, and annual basis (or more frequently if unanticipated issues arise), and will seek when appropriate NSF approval for any major change in accordance with the IDPO/IDDO change control process.

Table 2. Schedule: Intermediate Depth Drill Development

| | Completion Date | Milestones | Responsible Organization | Owner |
|---|---|---|---|---|
| | 07/31/10 | Approve start date for Intermediate Drill project | IDPO | Albert |
| | 1/15/11 | Create science requirements | IDPO | Albert |
| | 6/30/11 | Conduct feasibility study | IDDO | Shturmakov |
| | 11/30/11 | Create Concept-Schedule-Cost document | IDDO | Shturmakov |
| | 11/30/11 | Create engineering requirements | IDDO | Shturmakov |
| | 11/30/11 | Determine form of international collaboration | IDPO | Albert |
| | 12/31/11 | Review Concept-Schedule-Cost document | IDPO | Albert |
| | 08/31/12 | Keep IDD chief scientists informed of progress, and coordinate IDPO/IDDO resolution of any issues they raise regarding the drill | IDPO | Twickler |
| | 09/30/12 | Completion of design of major subsystems (sonde, winch, tower, buildings) | IDDO | Shturmakov |
| | 10/31/12 | Conduct engineering design review & report | IDDO | Shturmakov |
| | 11/30/12 | Review report of engineering design review | IDPO | Twickler |
| | 12/31/12 | Completion of detailed engineering design of remainder of subsystems | IDDO | Lebar |
| | 12/31/12 | Begin procurement and fabrication of drill system components | IDDO | Shturmakov |
| | 3/31/13 | Final engineering review of drill system | IDDO | Shturmakov |
| | 08/31/13 | Drill Fabrication Complete | IDDO | Shturmakov |
| | 12/31/13 | Create operation & maintenance documents | IDDO | Lebar |
| | 01/31/14 | Create field test plan | IDDO | Shturmakov |
| | 03/31/14 | Completion of integration testing, any required modifications, and report | IDDO | Shturmakov |
| | 06/31/14 | Complete field test in Greenland and report results | IDDO | Lebar |
| | 07/15/14 | Review report of field test | IDPO | Twickler |
| | 08/31/14 | Completion of modifications to drill as necessary | IDDO | Shturmakov |
| | 9/30/14 | Completion of Operating and Maintenance Plans | IDDO | Shturmakov |
| | 09/30/14 | Conduct project completion activities | IDPO | Albert |

***Cost***
The cost of the Intermediate Drill Development will remain within the budget for the NSF Cooperative Agreement with IDDO according to Table 3. Budget costs are described in more detail in the IDDO document "U.S. Intermediate Drill Concept, Schedule, and Costs" (attached as Appendix C) and in the IDPO/IDDO Annual Plans. Budget tracking and any change control activities are reported in IDPO/IDDO subsequent monthly and quarterly reports to NSF.

Table 3. Cost Estimates for IDD Development

| Fiscal Year | IDDO Budget | Drill Development Goal |
|---|---:|---|
| FFY 2011 | $85,000 | Feasibility study |
| FFY 2012 | $369,768 | Detailed Engineering Design |
| FFY 2013 | $973,292 | Drill Fabrication |
| FFY 2014 | $535,580 | Drill System Modifications After Field test |
| Total | $1,971,640 | Field tested drill ready for use |

IDDO has reduced the risk of cost overruns by leveraging both on the Danish intermediate drill and IDDO's past design and fabrication experience. In fact, much of the project's budgets are based on similarity to past projects. Experience by the CIC and IDDO considerably reduces the cost risk.

***Risks:***

The risk of the Intermediate Drill Development is reduced due to the planning described in the preceding sections, but still includes the following:

- The CIC drawings don't include later design modifications
- Availability of critical parts and materials
- Availability of key IDDO staff to work on projects

Project Management and Mitigation of Risks:

- Drawings without modifications: The phased funding approach and Detailed Engineering Design Phase in FY12 allowed IDDO necessary time to assess the impact of missing drawings or modifications. Although some drawings may be incomplete the overall design tasks will be considerably reduced from stand-alone design and production by IDDO
- Long lead parts and materials will be rapidly assessed to minimize schedule impact
- In FY12 IDPO and IDDO implemented a detailed project management system that includes project and resource scheduling. This gives management the ability to work resource and conflicting project commitments early, take action to mitigate negative impacts to the project, and report deviations from plan to the NSF.

**Appendices**

Appendix A.1 and A.2: Letters of International Collaboration

Appendix B: Science Requirements of the Intermediate Drill

Appendix C: IDDO internal documents:

- U.S. Intermediate Drill Concept, Schedule and Cost
- Engineering Requirements of the Drill
- IDDO Project Management Plan for IDD

CENTRE FOR ICE AND CLIMATE

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02-12 2011

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Dear Professor Mary Albert

Thanks for your letter proposing a partnership on design of Intermediate Drills. Through the last year we have initiated collaboration on the development of an Intermediate Depth Ice Coring Drill for the IDDO. During the spring 2011 Jay Johnson and Alex Shturmakov visited CIC and was informed about the Danish intermediate drill, The Hans Tausen Drill (HTD). Several of the drawings of the drill were shared with the IDDO staff. During the field season of 2011 Jay Johnson joined the drill team drilling a 410 m deep intermediate core at the NEEM camp on the Greenland Ice Sheet with the Hans Tausen drill,

We are very interested in continuing the partnership between the U.S. Ice Drilling Program Office and Ice Drilling Design and Operations (IDPO/IDDO), and the Danish Centre for Ice and Climate (CIC) on design and improving designs of Intermediate Depth ice coring Drills. The partnership will primarily be based on exchange of information and pooled expertise.

IDDO envisions the sonde for the drill to be based on the design of the CIC Hans Tausen Drill (Johnsen et al, 2007) while other drill systems and components are expected to diverge more significantly from the CIC design.

Because the CIC plans further enhancements to the HTD the partnership with IDDO will form an inspiring environment for advancing the design. The International Partnerships in Ice Coring Sciences (IPICS) White Paper “Ice Core Drilling Technical Challenges” identifies the need for ice coring drills and components and promulgation of best practices. The proposed partnership for development of the Intermediate Depth Drill is one example of an IPICS technological partnership.

CIC will provide, as needed and as available, drawings and information of the HT drill. Some of these have already been provided. In addition we envision to continue the close collaboration through visits and joint field seasons.

In turn, we envision that IDDO will collaborate with CIC and share design ideas on IDD and HTD with CIC. As the drilling technology develops in both groups, IDDO and CIC will strive to share engineering and technological advances, preferred suppliers and manufacturers, field opportunities and drilling personnel, as an ongoing sharing of drilling expertise.

Yours Sincerely

Dorthe Dahl-Jensen

Dorthe Dahl-Jensen
Professor, Niels Bohr Institute
University of Copenhagen
Centre leader for Centre for Ice and Climate

Ice Drilling Program Office
Dartmouth and the University of New Hampshire

February 2, 2012

Professor Dorthe Dahl-Jensen
Niels Bohr Institute
University of Copenhagen
Centre for Ice and Climate
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Denmark

Dear Professor Dahl-Jensen:

Thank you very much for sending drawings of the Hans Tausen drill (HTD) to engineers in the Ice Drilling Design and Operations group (IDDO). We in the Ice Drilling Program Office (IDPO) and IDDO are enthusiastic about ongoing exchange of information with Centre for Ice and Climate (CIC) during development of the Intermediate Depth Drill (IDD). The Hans Tausen drawings do help to move along the IDDO efforts for design modifications for the sonde. Other drill systems and components for the IDD are expected to diverge more significantly from the CIC design. I am sure that additional discussions between Jay Johnson and Steffen Bo Hansen while at WAIS Divide will have also generated enthusiasm about the new drill.

IDDO will be very active in this collaboration. IDDO will design a new anti-torque for the IDD, will update as necessary the drawings and specifications for entire Intermediate Depth drill sonde, and will provide the drawings and specifications to CIC for its use. IDDO will also provide any other drawings, specification, and analyses requested by CIC. IDDO will also collaborate with CIC on an ongoing basis to further improve and standardize the HTD and IDD and to identify suitable manufactures and vendors of components needed for the drills.

IDPO/IDDO efforts on drill development and construction are being funded by the National Science Foundation (NSF). The Intermediate Depth Drill itself, once constructed, will become part of the IDDO drill inventory that IDDO maintains and operates on behalf of NSF. As per NSF policies, "With respect to any subject invention in which the awardee retains title, the Federal Government shall have non-exclusive, nontransferable, irrevocable, paid up license to practice or have practiced for or on behalf of the U.S. the subject invention throughout the world." Per this policy, NSF, IDPO, and IDDO are not obligated to compensate CIC or others for input or contributions associated with developing the Intermediate Depth Drill. IDDO does not plan to file a patent on the drill, but will lead a paper written about the new drill. Intellectual contributions by CIC to the drill development or the publication will be appropriately attributed. Also, neither IDDO nor CIC is required to use the companies identified as preferred manufacturers and suppliers. This list of companies is an optional resource.

The International Partnerships in Ice Coring Sciences (IPICS) white Paper “Ice Core Drilling Technical Challenges” identifies the need for and standardization of ice coring drills and components and promulgation of best practices. The proposed partnership for development of the Intermediate Depth Drill is one example of an IPICS technological partnership. Needless to say, we are pleased about ongoing collaborations with CIC!

All the best,

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# Ice Drilling Program Office

Dartmouth – University of New Hampshire

| DOCUMENT IDENTIFICATION | |
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| Title: | **SCIENCE REQUIREMENTS: INTERMEDIATE ICE CORING DRILL** |
| Date: 1/10/2011 | Revision: Original Document |

| DOCUMENT APPROVAL | |
|---|---|
| Science Community: | E. Saltzman, E. Steig |
| IDPO: | Albert, Twickler, Souney |

| REVISION HISTORY (maintain last 3 versions) | | | |
|---|---|---|---|
| REV | DESCRIPTION | DATE | APPROVAL |
| - | Original Document | 1/10/2011 | See Above |
| | | | |
| | | | |

# Science Requirements: Intermediate Ice Coring Drill

Approved by IDPO January 10, 2011

*Background:*
The IDPO Science Advisory Board identified in the IDPO Long Range Science Plan a priority need to acquire an intermediate-depth drill for the U.S. ice coring program that is sufficiently portable that it can be used for coring at a wide variety of sites with production drilling in two field seasons or less, and be able to retrieve core from depths of interest for a variety of science goals. From discussions with the research community and discussions with IDDO staff, the following are the science requirements for the Intermediate Depth Ice Coring Drill:

**<u>Requirements</u>**
**Target depths: from the surface down to 1,500 m**
**Ice core diameter: 98 +/- 3 mm**
**Core length: 2 m**
**Minimum 10-m temperature at the site: -55$^{o}$C**
**Air transport type: Bell 212 or similar helicopter and/or Twin Otter**
**Replicate coring capability: no**
**Drilling fluid: drill should be compatible with existing fluids, e.g. Isopar-K or butyl acetate**
**Maximum field project duration: 2 field seasons**
**Core quality requirements:**

a. **Complete core recovery over entire borehole, as close as possible, including brittle ice**
b. **Ice pieces to fit together snugly without any gaps**
c. **In non-brittle ice, the packed core should have no more than 12 pieces of ice per 10-meter section of core**
d. **In brittle ice there may be a lot of pieces in a single ~ 1m core segment, but the pieces must fit together retaining stratigraphic order; more than 80% of the ice volume must be in pieces that each have a volume > 2 liters**

**Absolute borehole depth measurement accuracy: 0.2% of depth**
**Sonde inclination will not exceed 5$^{o}$**
**Field set-up time: the minimum that is realistically possible with a three-person effort at a small remote camp**
**System complete with receiving area for core from core barrel and ability to cut into 1-meter sections**
**A deep-field shelter for the drill should be identified**

*Discussion:*
This drill would be a modified version of the Hans Tausen (H-T) drill, with upgrades including a 2-m core length. The core quality requirements are those of the DISC drill. The requirements above can be achieved without use of a fiber optic cable; the drill could be built with a cable similar to the cable typically used by the H-T drill.

# U.S. Intermediate Depth Drill

## Concept, Schedule and Costs

Ice Drilling Design and Operations

November 21, 2011

## Introduction

In the IDPO Long Range Science Plan, the US science community has identified the retrieval of cores to depths of 1000-1500 meters for the IPICS 2k array and 40k network as a high priority. IDDO currently has drills capable of drilling to depths of approximately 300 meters with good core quality. The DISC Drill is capable of coring to depths of approximately 4000 meters with excellent core quality; the DISC Drill, however, is large and requires substantial logistics and infrastructure support which precludes its use for the coring of 1000-1500 and shallower holes. The science community, IDPO/IDDO, and NSF consequently agreed that a dedicated intermediate depth drill be developed.

Discussions in various meetings, such as the IDPO Science Advisory Board annual meeting and the Ice Core Working Group meeting, indicated that the science community and the scientists most likely to propose projects utilizing an intermediate depth drill preferred a relatively simple drill that could be transported by light aircraft with drilling activities being completed in not more than two field seasons for a 1500 meter core. The Danish Hans Tausen Drill is a model of such a drill and has been copied with some modification by the Antarctic Research Centre (ARC) at the Victoria University of Wellington, New Zealand. During the summer of 2010, IDDO sent one of its engineers to the NEEM camp in Greenland to witness the test of the New Zealand intermediate depth drill and to discuss the drill with the engineers and drillers from Denmark and New Zealand present at the test. The engineer shared his observations and recommendations concerning the development of a US intermediate depth drill with the IDDO staff and IDPO. The Danes on several occasions stated a willingness to assist IDPO/IDDO in the development of a US drill based on the Hans Tausen model.

IDDO continued discussions with the Danes into 2011 about modifications to the Hans Tausen Drill design for the development of the US intermediate depth drill. In February 2011, two of the IDDO staff traveled to Copenhagen and met with personnel from the Centre for Ice and Climate (CIC) at the University of Copenhagen, Denmark. During the visit, the Danes reviewed the design of the Hans Tausen Drill and the EPICA Deep Drill, which is based on the Hans Tausen Drill, and discussed with the IDDO personnel the modifications that would be beneficial to drill performance.

Technical discussions between IDDO engineers and CIC and ARC have continued through the finalization of the concept presented here.

In an effort to more fully define the equipment needs of the scientists, IDPO solicited input from the science community and from IDDO, and developed science requirements to guide IDDO in the design and configuration of the intermediate depth drill.

The purpose of this document is to formalize and update the conceptual design for the US intermediate depth drill along with a high level schedule and cost estimate for its development. This concept was first presented to IDPO in May 2011 and was the basis for the Intermediate Depth Drill Development Project proposed in the FFY 2012 IDPO/IDDO Program Plan submitted to NSF in August 2011, which was subsequently approved and funded by NSF. The drill described in the May document was also envisioned for use on a science project proposed to begin during the 2014-15 Antarctic field season. This document is not intended to be sufficiently detailed to allow the monitoring of progress in the execution of the development project; more definitive cost estimates and schedules have been completed for the FFY 2012 IDPO/IDDO

Annual Plan and will be completed for subsequent Program Plans during the development cycle of the drill.

## Science Requirements

The Intermediate Depth Drill will be designed and fabricated to meet the following requirements expressed by the science community:

- **Target depths:** up to 1,500 m
- **Ice core diameter:** 98 +/- 3 mm
- **Core length:** 2 m
- **Minimum 10-m temperature at the site:** -55$^{o}$C
- **Air transport type:** Twin Otter or similar size aircraft
- **Replicate coring capability:** no
- **Drilling fluid:** system should be compatible with existing fluids, e.g. Isopar-K or n-butyl acetate
- **Maximum field project duration:** one field season for max 1,000m depth and two field seasons for 1,500m depth
- **Core quality requirements:**
  - Complete core recovery over entire borehole, as close as possible
  - Ice pieces to fit together snugly without any gaps
  - In non-brittle ice, the packed core should have no more than 12 pieces of ice per 10-meter section of core
  - In brittle ice there may be a lot of pieces in a single ~ 2m core segment, but the pieces must fit together retaining stratigraphic order; more than 80% of the ice volume must be in pieces that each have a volume > 2 liters
- **Absolute borehole depth measurement accuracy:** 0.2% of depth
- **Bore hole inclination:** not to exceed 5$^{o}$

While not science requirements per se, the science community also indicated that it would prefer the equipment designed and assembled by IDDO include shelters for the drill and core handling facilities to allow cores to be cut to 1-meter lengths for storage and shipping. These ancillary facilities are included in the project cost estimate and schedule.

## Conceptual Design

Early in discussions about a US Intermediate Depth Drill, the "downsizing" of the DISC Drill was mentioned as a possibility. Because of the sophisticated electronics built into the DISC Drill, an intermediate depth drill based on that design would allow the collection of a great deal of data while drilling and would facilitate the addition of a replicate coring capability. However, given the requirements that the drill be transportable by Twin Otter and able to complete coring to 1500 meters within two seasons, IDDO ruled out a design based on the DISC Drill.

Research by IDDO indicated that the only existing model for an intermediate depth drill of the type desired by the US science community was the Hans Tausen Drill developed by CIC. Basing the design on the simple, proven technology of that drill would allow IDDO to develop the US Intermediate Depth Drill more cost effectively and in a timelier manner than developing an entirely new concept. In addition, the Danes indicated a willingness to work with IDDO in modifying/upgrading the design of their intermediate drill. The design of the US Intermediate Depth Drill, therefore, will be similar to the Danish Hans Tausen Drill and the recently completed intermediate depth drill built by the Antarctic Research Centre of Victoria University of Wellington. Major components of the Intermediate Depth Drill System will include:

- Drill Sonde (**Figure 1; see also Figure 3 in Attachment 1)**
    - Redesigned anti-torque with enclosed slip ring
    - Pressure tube/motor section with all internal components and bulkheads (no electronics, 900W motor)
    - Hollow shaft with screen
    - Chips chamber
    - Booster (short auger section that helps pack chips in the chips chamber)
    - Core barrel (sized for 2m core)
    - Provisions for optional pump (positive displacement pump to aid in fluid pumping)
    - Dry drill flight clearance
    - Cutter head with three cutters and three core dogs
    - Hardened steel cutters
    - Carbide cutting edge cutters (edge brazed on)
- Drill Cable – 5.7mm (0.223 in.) dia., 3 conductors
- Drill Winch (**Figure 2**) –powered by 4.5kW motor with a drum capacity of 1,600 m of cable to enable drilling to 1,500 m depth. Capable of 1 m/s average line speed and 1,300 lb. continuous pull (2,900 lb. maximum pull on first wrap)
- Tilting Tower (**Figure 3**) – base mounts directly to the winch; the tower will have an instrumented crown sheave-encoder and a load pin. Tower will be 5m long and require a 3.5m long x 1 wide x 3m deep slot for tilting. The tower will be modular to allow transport in Twin Otter. Drip pans will be included for fluid containment.
- Control Box – single box to run both the winch and the drill; includes payout and load meters and output for data graphing/logging.
- Power System – three 10kW diesel engine driven generators (including one spare) and the power distribution system
- Chip Handling System – a centrifuge, chip bucket hoist system, and a chip transporting system.
- Drill Fluid Handling System – for use with a single component drilling fluid; includes pump, hoses, drip pans, electrical system, and cable vacuum attachment to remove fluid from cable (vacuum unit will be common with core liquid removal system).
- Core Processing System – includes core barrel puller, trays for core handling, core vacuum, core saw, and core tables.
- Pilot Hole System – includes reamers and casing installation tools

- Structures (**Figure 4 and 5**) – one 16’ x 72’ Polarhaven for housing the drilling and core handling/processing operations and a second 10’ x 16’ Polarhaven for housing the generators.
- Safety Equipment – a portable oxygen monitor and a ventilation system for use in the drilling structure as well as other necessary safety equipment.
- Tools – hand tools and power tools for performing basic maintenance and repairs, includes a cable tensioner to allow spooling of cable in the field.
- Drill Recovery System – tools such as “fishing” tools and cable “grabbers”
- System for Warm Ice Drilling – a core barrel warming bath to facilitate the removal of core frozen to the core barrel
  Cargo Handling System – a device for loading and unloading cargo from a Twin Otter and various cases, crates, etc. to protect equipment during shipping

**Figure 1.**
**Hans Tausen Drill – Sonde**

**Figure 2.**
**Conceptual Solid Model of the IDD Winch**

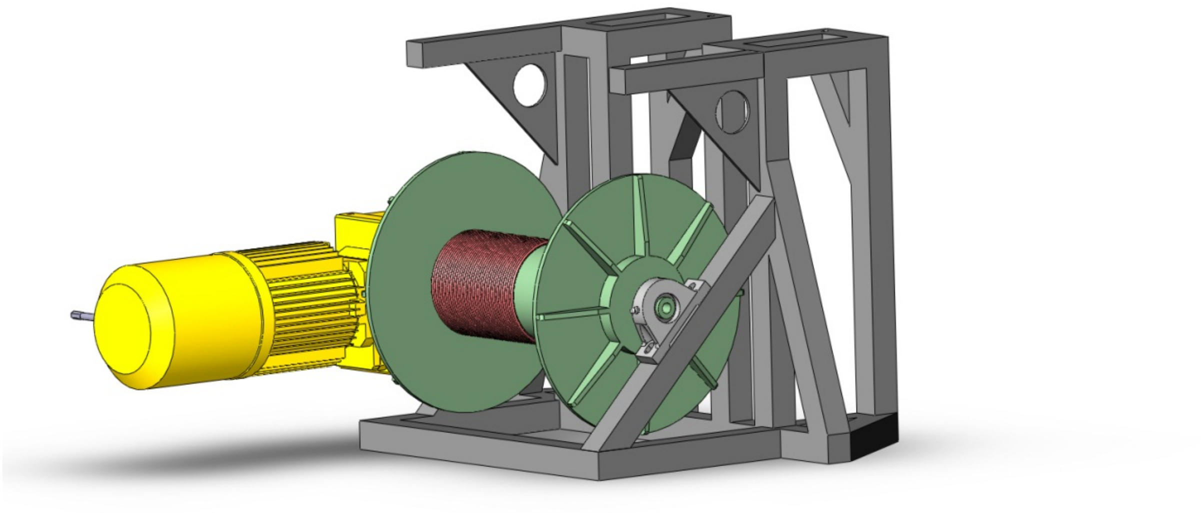


**Figure 3.**
**Conceptual Solid Model of the IDD Winch and Tower**

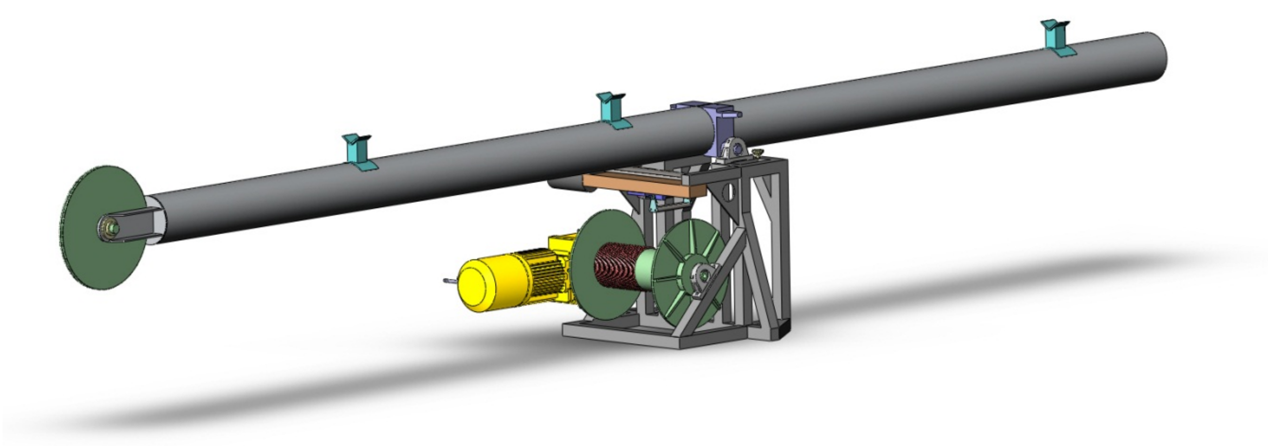


**Figure 4.**
**Conceptual IDD System – Isometric View**

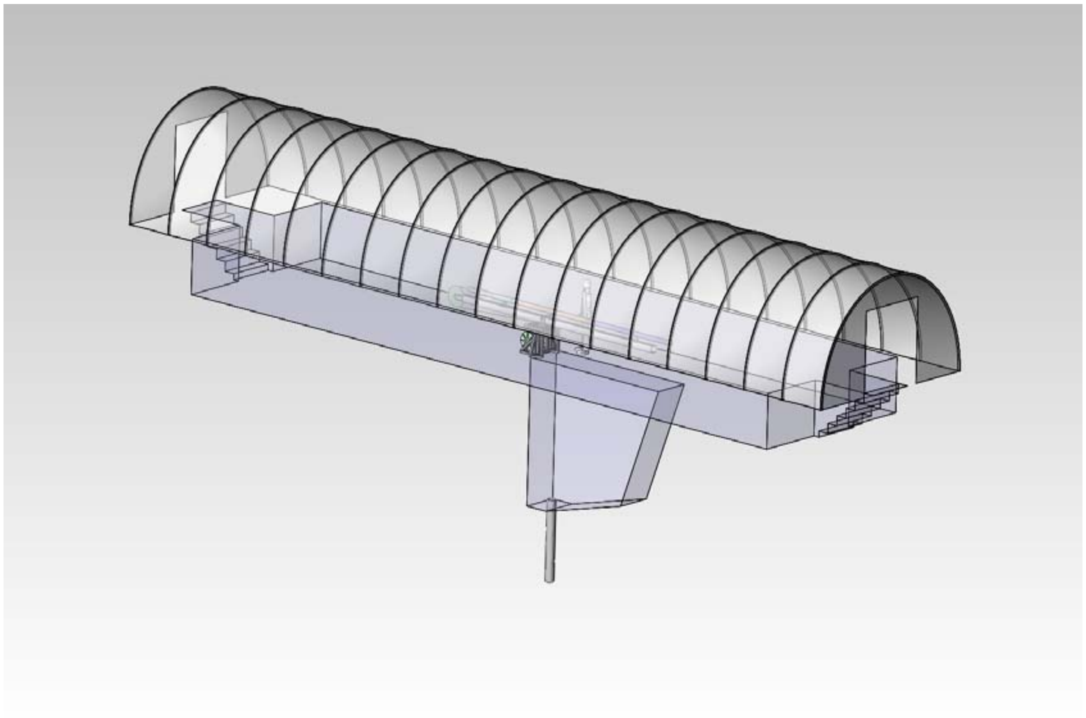
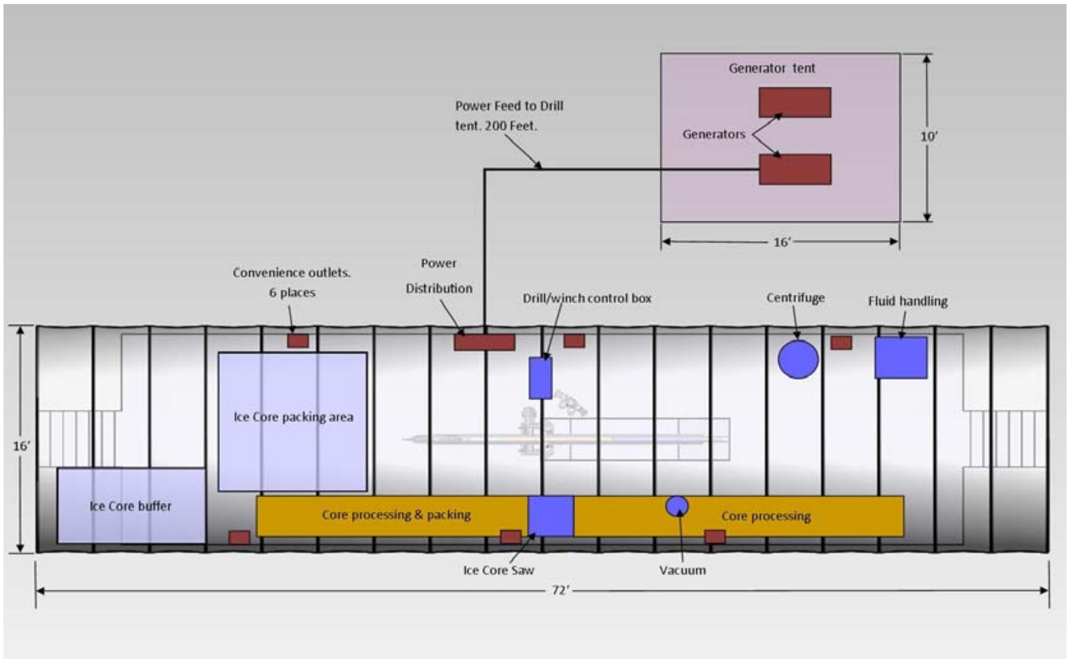


**Figure 5.**
**Conceptual IDD System – Field Layout**



## Project Schedule

IDDO anticipates that the development of the Intermediate Depth Drill can be started during FFY 2012 and completed in FFY 2014 in time for a project in the 2014-15 Antarctic field season. It appears that the project can be completed using the baseline funds provided for in the IDDO Cooperative Agreement. IDDO developed a rough schedule to inform the discussion of the timing of the development of the drill and its availability for production drilling. A detailed project schedule, which will be used in the management of the drill development project, has been developed for the Intermediate Depth Drill for the FFY 2012 Annual Plan in conjunction with the schedules for other projects anticipated for FFY 2012. The schedule has been built upon the milestones listed in **Table 1**.

**Table 1.**
**Major Milestones in the Development of the US Intermediate Depth Drill**

| Milestone Description | Expected Completion Date |
|---|---|
| Approval of Intermediate Drill Conceptual Design | 05/31/11 |
| Submission of IDPO-IDDO FFY 2012 Annual Plan to NSF | 08/31/11 |
| Begin Detailed Design of the Drill Based on Conceptual Design | 10/01/11 |
| Submission of Formal Conceptual Design Document to IDPO for Approval | 11/30/11 |
| IDD System Design Verification Review – Major Drill Subsystems | 07/20/12 |
| Complete Detailed Design | 12/31/12 |
| IDD System Design Review – Ancillary Systems | 01/18/13 |
| Complete Fabrication of the Drill | 09/30/13 |
| Draft of Operating and Maintenance Documentation | 12/31/13 |
| Integration of Drill System (including integration test) | 03/31/14 |
| Complete Field Testing | 06/15/14 |
| Review of Test and Needed Improvements | 06/25/14 |
| Complete Improvements and Modifications after Testing | 08/31/14 |
| Finalize Operating and Maintenance Documentation | 09/30/14 |

## Drill System Costs

The development of the Intermediate Depth Drill is estimated to cost $1,878,640. The estimate of the budget for designing, construction and testing of IDD is shown in **Table 2**.

**Table 2.**

**Estimated Cost of Intermediate Depth Drill Development**

| | FFY 12 | FFY 13 | FFY 14 | Total |
|---|---|---|---|---|
| **Materials and Equipment** | | | | |
| Drill Sonde | 9,200 | 278,640 | 25,000 | 312,840 |
| Pilot Hole Tools | 0 | 17,200 | 0 | 17,200 |
| Winch | 12,706 | 108,300 | 0 | 121,006 |
| Tower | 21,000 | 0 | 0 | 21,000 |
| Drill/Winch control box | 0 | 9,000 | 0 | 9,000 |
| Power System | 0 | 42,852 | 0 | 42,852 |
| Chip Handling | 24,800 | 400 | 0 | 25,200 |
| Drill Fluid Handling | 0 | 15,817 | 0 | 15,817 |
| Core Processing | 0 | 24,665 | 0 | 24,665 |
| Structures | 4,200 | 31,523 | 0 | 35,723 |
| Safety | 0 | 6,206 | 0 | 6,206 |
| Tools | 7,500 | 5,075 | 0 | 12,575 |
| Drill Recovery | 0 | 1,860 | 0 | 1,860 |
| Drilling Warm Ice | 0 | 4,300 | 0 | 4,300 |
| Cargo Handling | 0 | 17,000 | 0 | 17,000 |
| | | | | |
| Materials and Equipment | 79,406 | 562,838 | 25,000 | 667,244 |
| Labor and Benefits | 159,287 | 208,968 | 135,916 | 504,171 |
| Travel | 7,000 | 7,000 | 0 | 14,000 |
| Overhead | 124,075 | 194,486 | 78,006 | 396,567 |
| **Total - Drill System** | 369,768 | 973,292 | 238,922 | **1,581,982** |
| | | | | |
| System test (including overhead) | 0 | 0 | 138,460 | 138,460 |
| System Modifications (10% of Drill System Cost) | 0 | 0 | 158,198 | 158,198 |
| **Total - Development** | 369,768 | 973,292 | 535,580 | **1,878,640** |

A discussion of the cost estimate line items follows.

*Materials and Equipment*

Based on the conceptual design for the Intermediate Depth Drill, costs for the major components – both materials and capital equipment – were estimated based on historical costs for similar components or from vendor estimates for similar components. Discussion of costs for materials and equipment requiring explanation follows.

Sonde – The estimated cost for the drill Sonde includes the Sonde itself and applicable spares. The estimate also includes 6 sets of hardened steel cutters, 4 sets of brazed carbide cutters, 6 sets of core dogs, re-designed and fabricated Anti-Torque section of the Sonde and “Evegrip” cable termination.

Winch – The estimated cost for the winch includes not only the winch, but two drill cables, one of which is a spare, a level-wind assembly, and a laptop computer. The winch is expected to be fabricated from components (e.g., drum and motor) and the estimate includes the cost of those components but not their assembly. The cables are "off-the shelf" items as is the computer.

Control Box – The estimate for the control box (one control box controls both winch and drill Sonde) is for the materials for two boxes, one of which would be a spare.

Power System – A preliminary electrical load calculation was made based on the known power requirements for electrical components similar to those that will be used in the drill system. The power budget indicated that approximately 20 KW would be required for the entire drilling – core handling system. For the cost estimate of the power system, generators much larger than 10 KW were determined to be too large to be transportable by Twin Otter. Three generators are envisioned with two operational and the third as a spare. The estimate also includes the necessary components for power distribution.

Chip Handling – A centrifuge to extract drill fluid from the ice chips is the main component in the chip handling system. The unit used for the estimate is commercially available. Other components of the system are for collecting and moving the chips; these are also commercially available.

Structures – The estimate for components for the structure to house the drilling and core processing operations was based on the costs of shelters sold by Weatherhaven; two structures – one for the drill and core processing operations and one for the generators are planned. The estimate also includes the costs for such items as a soft-sided drill control room within the operations structure, floor mats, and hand railing to prevent falls into the slot.

To the extent possible, components were classified as either materials (over-headed) or capital equipment (not over-headed).

*Labor and Benefits*

The estimate for labor and benefits includes the salaries along with the fringe benefits of SSEC employees involved in the development of the drill system (design, fabrication, and project management). It also includes the costs of services of other UW employees and subcontractors who might be involved in design or fabrication activities. It does not include the labor costs associated with the field testing of the drill system.

*Travel:*

A total of $14,000 was provided in the cost estimate for project personnel's travel to work with suppliers and the Centre for Ice and Climate.

*Overhead:*

The University of Wisconsin's approved indirect cost (overhead) rate of 50.5% was applied to materials, labor and fringe benefits, subcontractor services, and travel. It was not applied to those components whose cost was expected to exceed $5,000, e.g., the Weatherhaven shelters.

*System Test:*

IDDO plans to conduct a test of the drill system in the spring of 2014. As currently planned three IDDO drillers (probably a combination of IDDO engineers and contract drillers) would test the drill system in Greenland for about a month. The estimate includes the shipping of the equipment to and from Scotia, NY, travel for the drillers/engineers, salary and fringe benefits for the IDDO personnel and the costs of the contract driller's services, and any needed supplies. It also includes UW overhead at 50.5%.

*System Modifications:*

IDDO anticipates that after the field test of the Intermediate Depth Drill, the system will require some modification and repair to make it ready for production drilling. Since the drill concept is generally proven, IDDO has allowed 10% of the estimated drill system development cost to make those modifications and repairs. Modifications to the DISC Drill after its test in Greenland and before its first production season were about 23% of the original development costs. Since the Intermediate Depth Drill is less complex than the DISC Drill, 10% of the development cost was deemed appropriate.

The Grand Total does not include consumables provided by IDDO and materials that are normally provided by a logistics group such as RPSC for a field project – borehole casing, ethanol, drilling fluid, etc. Table 3 provides an estimate of those costs for a 1500-meter hole.

**Table 3.**
**Additional Costs for Materials and Supplies Costs Associated with a 1500-Meter Core**

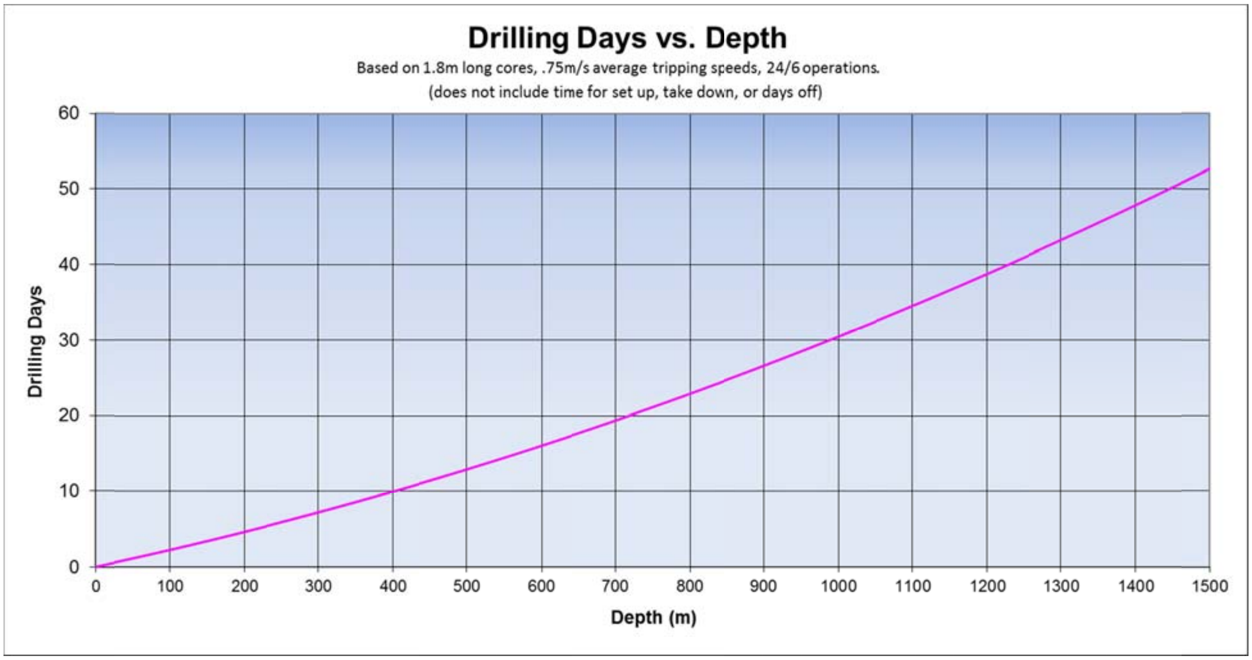
| Item | Cost |
|---|---|
| Pilot hole casing (100m) | 11,200 |
| Netting for brittle ice (600m) | 1,699 |
| Lay flat tubing for deploying ethanol water solution in the drill (warm ice drilling) | 75 |
| Ethylene glycol, 4L (for unsticking a drill) | 340 |
| Ethanol, 55 gallon drum, (for deicing, drilling warm ice, and unsticking a drill) | 865 |
| Drilling fluid, Isopar-K, enough to maintain a fluid filled borehole to 1500m (120 drums) | 62,400 |
| **Total** | **76,579** |

Not included in the table is fuel for the generators, which is generally supplied from the logistics provider's inventory. Fuel usage is estimated to be approximately 5 l/hr. while drilling (2 x 10 kW gens at 75% load) or approximately 6,200 liters for drilling a 1500-meter hole.

## Drill Performance

The projected time to drill to the depth of up to 1,500 m is shown in **Figure 4**. The drilling time does not include the time necessary to unpack and assemble the drill system or the time to disassemble the system and pack all equipment. The operation depicted is based on 24-hour per day operation.

**Figure 4.**
**Estimated Time to Core to Depth**




IDDO estimates that it would take a drill crew of three or four people less than two weeks to unpack and set up the drill system at a remote site at the beginning of a field project and approximately 1 week to disassemble and pack the drill at the end of the project. For field projects lasting more than one season, most equipment would be left to "winter-over".

## Logistical Needs

The Intermediate Depth Drill would be designed and constructed to be transportable by Twin Otter or helicopter. The estimated total Intermediate Drill System weight is approximately 12,451 lbs., and the total cargo volume is 811 cu ft.

These estimated weights and volumes include:

- Drill sonde – 460 lbs. & 22 cu. ft.
- Drill winch and cable including level-wind) – 1160 lbs. & 11 cu. ft.
- Tilting tower – 475 lbs. & 43 cu. ft.
- Power system – 2175 lbs. & 84 cu. ft.
- Structures – 4030 lbs. & 354 cu. ft.

The approximate total number of Twin Otter flights required to transport the drill system, not including items in Table 3 and generator fuel, is estimated to be in the range of 6-8. This number is based on the standard fuel capacity with no optional cabin auxiliary tank or wing tanks. Cargo handling equipment will include a 1,000 lb. capacity scissor lift for loading/unloading Twin Otter planes. The two heaviest pieces of equipment that will be handled in the field are the winch drum with the 1,600m of cable (estimated weight under 850 lbs.) and a power generator with the weight of 650lbs. The WeatherPorts for the building for the drill (16'wide x 72' long, ~ 150 cubic feet) and for the building for the generators (10' wide x 16' long, ~ 23 cubic feet) will be built in pieces that could be transportable by Twin Otter, assembled in the field and handled by the scissor lift.

Total drilling fluid requirements based on 132 mm bore hole diameter, 1500 m deep borehole and 33% loss rate are 120 drums x 336 lbs./drum = 40,320 lbs. It would take approximately 20 Twin Otter flights to deliver all drilling fluid to the field.

Approximately 35 Twin Otter flights would be required to deliver all the necessary equipment, drilling fluid, generator fuel and supplies. This number does not include required flights for the camp put-in and would be strongly affected by the distance between the field camp and the point of departure, along with the field camp altitude.

**<u>Attachments</u> (papers from Annals of Glaciology, Vol. 47, 2007)**

1. Sigfus J. Johnsen, et al. The Hans Tausen drill: design, performance, further developments, and some lessons learned; p.89-98
2. Robert Mulvaney, et al. The Berkner Island (Antarctica) ice-core drilling project; p. 115-133

Attachment 1.



# The Hans Tausen drill: design, performance, further developments and some lessons learned

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**ABSTRACT. In the mid-1990s, excellent results from the GRIP and GISP2 deep drilling projects in Greenland opened up funding for continued ice-coring efforts in Antarctica (EPICA) and Greenland (NorthGRIP). The Glaciology Group of the Niels Bohr Institute, University of Copenhagen, was assigned the task of providing drilling capability for these projects, as it had done for the GRIP project. The group decided to further simplify existing deep drill designs for better reliability and ease of handling. The drill design decided upon was successfully tested on Hans Tausen Ice Cap, Peary Land, Greenland, in 1995. The 5.0 m long Hans Tausen (HT) drill was a prototype for the ~11 m long EPICA and NorthGRIP versions of the drill which were mechanically identical to the HT drill except for a much longer core barrel and chips chamber. These drills could deliver up to 4 m long ice cores after some design improvements had been introduced. The Berkner Island (Antarctica) drill is also an extended HT drill capable of drilling 2 m long cores. The success of the mechanical design of the HT drill is manifested by over 12 km of good-quality ice cores drilled by the HT drill and its derivatives since 1995.**

## INTRODUCTION

In 1994 a new palaeoclimatic European Union (EU) project 'European Project for Ice Coring in Antarctica' (EPICA) was initiated, in part building on the momentum of the successful European Greenland Icecore Project (GRIP) (GRIP Members, 1993) both in terms of drilling technology and scientific know-how. The plan was to recover deep cores at Dome C (EPICA Dome C (EDC) core (EPICA Community Members, 2004) and in Dronning Maud Land (EPICA DML (EDML) core) (EPICA Community Members, 2006). The Glaciology Group (now the Ice and Climate Group) of the University of Copenhagen (UCPH) that had organized the GRIP drilling project was assigned the task of providing ice-drilling capability for the EPICA project. The drill should also serve the North Greenland Icecore Project (NorthGRIP) (Dahl-Jensen and others, 2002; NorthGRIP Members, 2004), a new deep drilling project in Greenland, organized and significantly funded by the UCPH group. This opened up the possibility of testing new design features in Greenland prior to the next drilling season in Antarctica, as well as training new drillers for Antarctic work. All these projects became highly successful in terms of drilling performance and scientific outcomes.

The ISTUK drill (Johnsen and others, 1994) used in the GRIP project was considered unsuited for the very cold Antarctic temperatures, due to both the battery pack and some special rubber gaskets that would not seal properly at the very low temperatures expected in Antarctica. Thus it was decided to aim at a simpler drill design for the EPICA project. This had been fully specified by the UCPH group when they accepted the task. The EPICA steering committee requested that L. Augustin (L.A.) and P. Journé (P.J.), of Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE), Grenoble, France, should work with S.J. Johnsen (S.J.J.) and S.B. Hansen (S.B.H.) on the drilling task, and the Italian group from Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA) should build new drill electronics under the supervision of the late N. Gundestrup from the UCPH group, who was also the chairman of the EPICA drilling group.

Successful experiments with the 3 in (7.62 cm) UCPH shallow drill (Johnsen and others,1980) in a wet hole on Summit Greenland in 1993 pointed to a fully acceptable solution. The shallow drill was modified for drilling in a wet hole by removing the upper half of the 2 m long core barrel and making a space for a chips chamber with a filter at the top. The drive shaft passed through the chips chamber to the core barrel. This design was used in the Icelandic

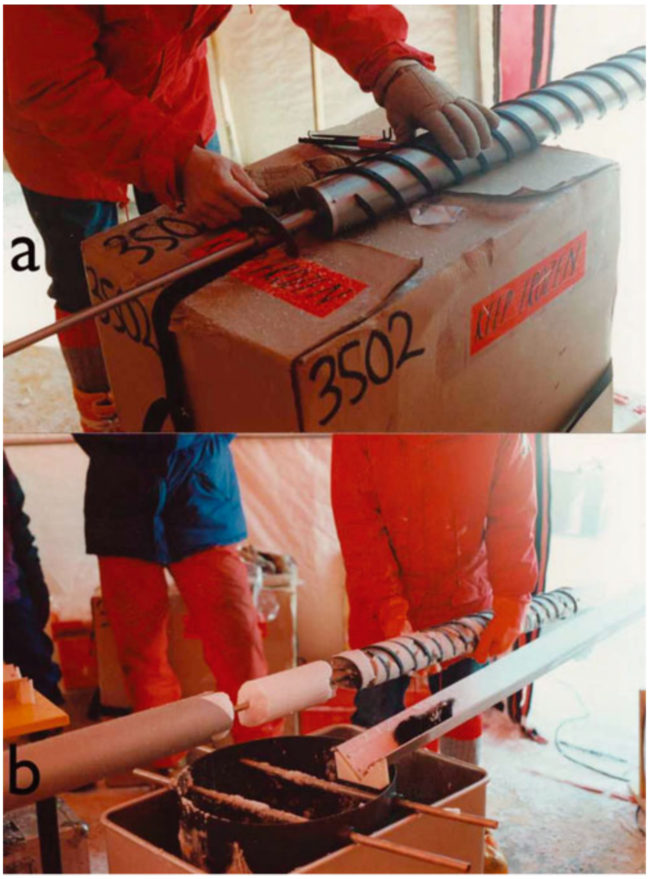


**Fig. 1.** The modified UCPH shallow drill. (a) Drive shaft, booster and shortened inner core barrel. (b) After a normal successful run, chips chamber, booster and spirals are packed with chips. The chips fall into the black PVC jug with a fine filter at bottom; the liquid is collected in the aluminium bucket.

**Table 1.** Hans Tausen drill, main dimensions (mm). ID: inner diameter; OD: outer diameter

| | | | |
|---|---|---|---|
| Hole diameter, wet | 129.6 | Outer-barrel length | 1910 |
| Hole diameter, dry | 126.0 | Hollow-shaft ID | 20.0 |
| Core diameter | 98.0 | Hollow-shaft OD | 30.0 |
| Drill-head ID | 99.0 | Chips-chamber ID | 110.3 |
| Core-barrel ID | 100.0 | Chips-chamber OD | 114.3 |
| Core-barrel OD | 104.0 | Chips-chamber length | 1586 |
| Core-barrel length | 1732 | Pressure-tube length | 600 |
| Outer-barrel ID | 113.0 | Anti-torque length | 900 |
| Outer-barrel OD | 118.0 | Outer-barrels length | 3494 |

Bardarbunga drill (Ámason and others, 1974; Theodórsson, 1976) and was later adopted by the designers of the Japanese Antarctic Research Expedition (JARE) deep drill (Suzuki and Shimbori, 1986; Suzuki, 1994; Tanaka and others, 1994). In the bottom of the chips chamber a Suzuki booster (Hancock, 1994) for compacting the chips was mounted on the drive shaft (Fig. 1).

The test showed that the usual cracking of a dry drilled core after passing a certain depth (presumably due to less manageable and increasingly finer chips) could be entirely prevented, at least to the maximum tested depth of 230 m, by having liquid (D60 lamp oil) in the hole. At these depths the liquid only needs to cover the drill and seems to lubricate the entire chips transport process. Figure 2 demonstrates the core quality before and after the liquid had been added to the hole at 160 m depth.

## MAIN DESIGN FEATURES

Having reviewed existing mechanical drill designs in light of the drilling experience of UCHP, it was decided that the new deep drill for the EPICA and NorthGRIP projects should be based on the same concepts as the Bardarbunga drill (Árnason and others, 1974) as well as on several design features of the ISTUK and UCPH shallow drills (Johnsen and others, 1980, 1994; Gundestrup and others, 1984). The Polar Ice Coring Office (PICO) ice-coring drill (Hancock, 1994) and the JARE deep drill (Tanaka and others, 1994) were designed using similar general concepts.

The main features of the new drill (Fig. 3) were an inner core barrel with spiral flights, a 100 mm drill head scaled up from the shallow drill and an outer barrel with inside grooves. The cuttings were to be stored in a chips chamber at the top of the core barrel. A 30 mm diameter hollow shaft with several holes and a fine-mesh screen (0.5–1.0 mm) clamped on the outside for filtering the chips also acts as a drive shaft extending through the chips chamber. Important modifications were incorporated to ensure fast tripping (better than 1 m s$^{-1}$) of the drill in the hole, as was the case with the ISTUK drill. This goal was achieved by having a

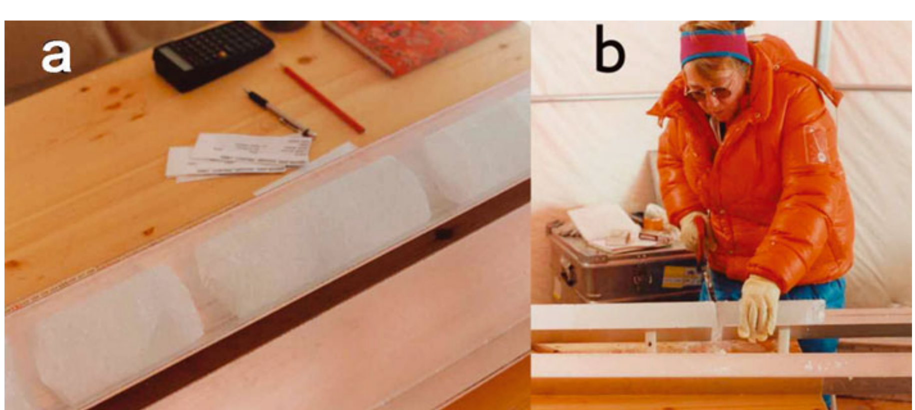


**Fig. 2.** Summit 1993 drill test with UCPH shallow drill: (a) broken and internally fractured core from dry drilling at 160 m; (b) perfect unbroken core from wet drilling at a similar depth.


**Fig. 3.** The major components of the HT drill. The first version, a prototype for the deep NorthGRIP and EPICA drills, was tested on Hans Tausen Ice Cap in 1995; it did not have the pump or the bayonet coupling installed. See text for further explanation.

minimum of 5.8 mm clearance between the outer drill barrel and the hole wall. Furthermore, the end pistons of the chips chamber were designed as valves that could be opened (to almost one-third of the drill cross-section) and closed by rotating the drive shaft backwards and forwards. The valves were to be left open until the drilling started, so that, when lowering, the liquid can bypass the narrow, high drag zone between the outer barrel and the hole wall by flowing through a much larger cross-section inside the core barrel and the chips chamber. Easy and fast surface operations were achieved with only two operators, by using the tilting-tower concept of the UCPH shallow and ISTUK drills.

A prototype drill incorporating all these features was built in 1995. The final drawings were made by L.A. with the Euclid drafting program at LGGE in Grenoble. The tubes below the pressure tube along with the inner parts were built by subcontractors in the Grenoble area and overseen by L.A. The drill heads, cutters and shoes were made by H. Rufli (H.R.) in Bern, Switzerland, scaled up from the UCPH shallow drill (Fig. 4). The electronic parts including motor and gear section were imported either from the UCPH shallow drill or the ISTUK drill, and the anti-torque from the ISTUK drill. The overall drill length of 5.0 m with the short pressure tube was inspired by the size of an existing drilling tent and also made the drill easily transportable in a Twin Otter or similar aircraft. The drill can also be modified for dry drilling; the only change needed is to mount a specially designed dry drill head with narrower cutters, also made by H.R., giving a minimum of 4 mm clearance between the drill and the hole wall. Table 1 lists most of the drill dimensions.

## THE HANS TAUSEN DRILL TEST

Two members of the EPICA drilling group from LGGE (L.A. and P.J.) were invited to participate in the Nordic Hans Tausen Project (Hammer and others, 2001) organized by the UCPH group, where they assisted S.B.H. and S.J.J. in testing the new drill on Hans Tausen Ice Cap, Peary Land, Greenland.

The drill prototype was equipped with a Suzuki booster and a simple coupling of the core barrel, i.e. no bayonet coupling (cf. Figs 3 and 10). The drill was mounted on the shallow-drill winch base with a 3.5 m long tower and 400 m of cable (Figs 3 and 5a). The electronics were borrowed from the shallow drill, with a 160 V d.c. motor mounted inside a short pressure tube on the old ISTUK drill gear section. The anti-torque section was also imported from the ISTUK drill. The drill, tower and general set-up is shown in Figures 5 and 6.

As the HT dry drill head was not ready, the initial dry drilling was done with the UCPH shallow drill down to

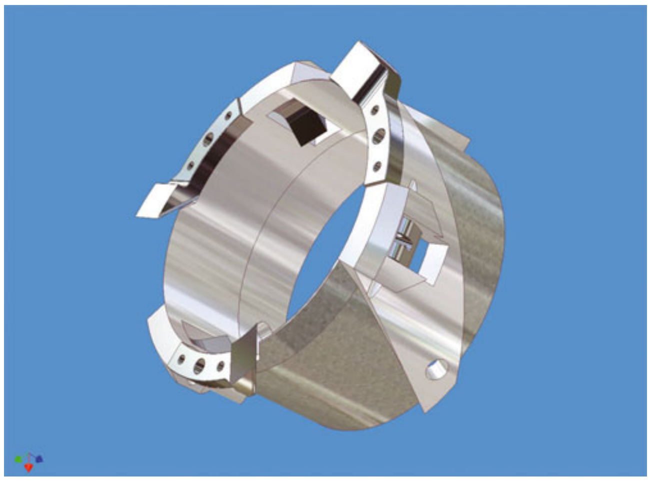

**Fig. 4.** The 4 in (10.16 cm) Hans Tausen drill head is blown up from the one used in the 3 in UCPH shallow drill. The shoes (not shown) that control the pitch are located right behind the cutters for best results. The wet and dry version are slightly different, cutting 129.6 mm and 126.0 mm holes respectively and 98 mm core in both cases. The cutter widths are thus 15.8 mm for the wet and 14.0 mm for dry head. The cutters normally used have a relief angle of 15° and a cutting angle of 45°.

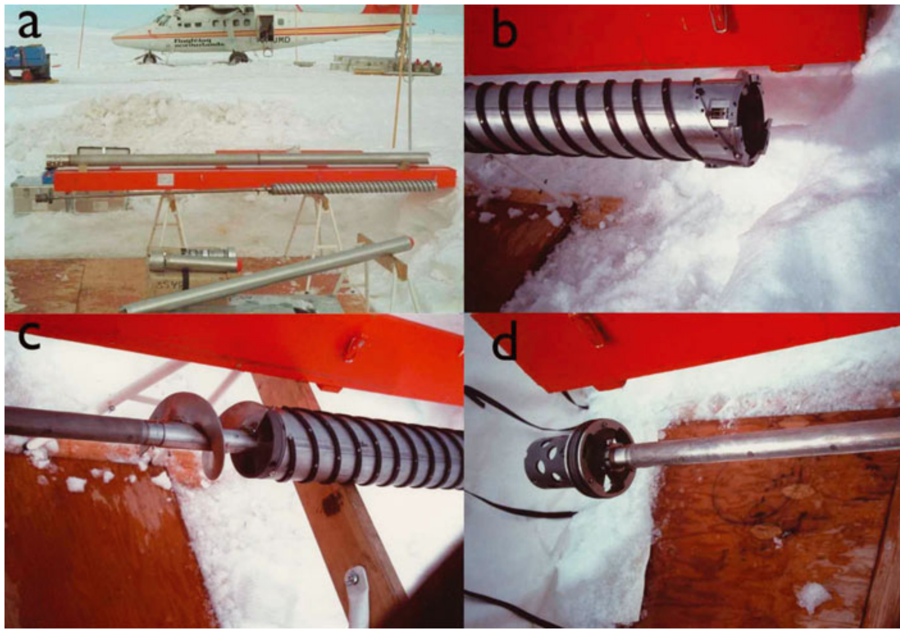


**Fig. 5.** From the Hans Tausen Ice Cap 1995 drill test. (a) The tubes in the foreground are the reamer units; the 3.5 m long outer drill barrel sits on the long transport box; on the side are the inner drill parts, hollow shaft, booster and core barrel. In the background we see the 8 kW generator to the left, the Twin Otter and the cargo line to the right. (b) Drill head mounted on core barrel with polyethylene spirals. The extra flights on the drill head extending to the hole wall produced immediate packing. (c) Top of core barrel, hollow shaft with filter sleeve and booster mounted. (d) Top valve and coupling cup mounted on top of hollow shaft. The valve consists of two circular discs with large specially designed openings and Teflon seals on the outside. The upper disc is fixed to the shaft, and the lower disc can rotate 120° relative to the other, helped by the friction between seal and outer barrel; in the end positions the openings are either aligned or closed.

106 m. The hole was reamed up to 130 mm with the reamer set seen in Figure 5a. Three more reamers come with the drill that can ream up to 25 cm diameter for standard casing (Johnsen and others, 1994). As very little densifier was available, the drilling liquid used was mainly odourless lamp oil (D60). We never had more than a 50 m liquid column in the hole, adding new liquid when the column was lowered to 10 m. There was no casing, so the liquid was dumped in the hole using a 50 m long plastic hose. Due to the low liquid density (880 kg m$^{-3}$), the cuttings left in the hole remained at the bottom for easy retrieval in the next run, a situation the polyethylene spirals and the booster could easily cope with.

The drill test went extraordinary well, almost all the new drilling concepts worked as hoped for and we recovered 344 m of perfect core, with typical run length of 1.6 m, during 3 weeks of drilling, working one daily 10 hour shift. Unexpectedly, the core quality turned out to be independent of the liquid pressure at the bottom of the hole. The ice temperature at the ice–bedrock interface was –17°C. The friction between drill and liquid was very close to what had been predicted by P.J.'s liquid-flow calculations, making 1 m s$^{-1}$ drill velocity an easy goal to achieve, both when travelling up and down the hole.

One improvement, however, did not work as expected, but taught us a lesson. As an experiment, we extended the flights on the drill head out to the hole wall (Fig. 5b) in order to better guide the cuttings away from the cutters towards the spiral transport system. This 'improvement' made the chips pack immediately on the drill head, actually confirming earlier experiences made with the ISTUK drill. New 'improved' drill heads, manufactured later in the EPICA drilling project, with more confined conduits for guiding the chips also had the same problem. What we had achieved was to prevent free mixing of fresh cuttings and liquid, which is imperative for proper lubrication and moving of the chips. We also learned later on, when using the pump (discussed below), that the chips–liquid mixture needs constant stirring in order to avoid separation of the two components (ice and liquid), which inevitably results in blocked chip transport, hard packing of the chips on the drill head and a lost run.

## FURTHER DEVELOPMENTS

During the NorthGRIP and EPICA projects, the drilling group met after each boreal and austral drilling season in order to analyze the lessons learned and to decide on possible improvements to the design. As soon as the highly successful 1995 test field season ended, the drilling group decided that the only change needed for building an efficient deep drill was to make a longer version of the HT drill with all other design features mostly unchanged. The 1.7 m long core barrel and the 1.6 m long chips chamber of the prototype HT drill should be made as long as 4 m each in the new deep drill in order to get sufficient core production. This drill was ready for testing at NorthGRIP in 1996 using slightly modified ISTUK electronics and the drill tower from the GRIP drilling project on Summit Greenland. At the same time we tested the new winch intended for the EPICA drilling at Dome C.

The performance of the new drill was far below our expectations. The drilled cores were long and unbroken, but the chip transport between the drill head and the chips chamber was very inefficient, leaving behind too high a proportion of the cuttings from each run, resulting in problems such as difficult penetration. In spite of the problems that summer, however, we installed the casing and managed to drill to 350 m at Summit.

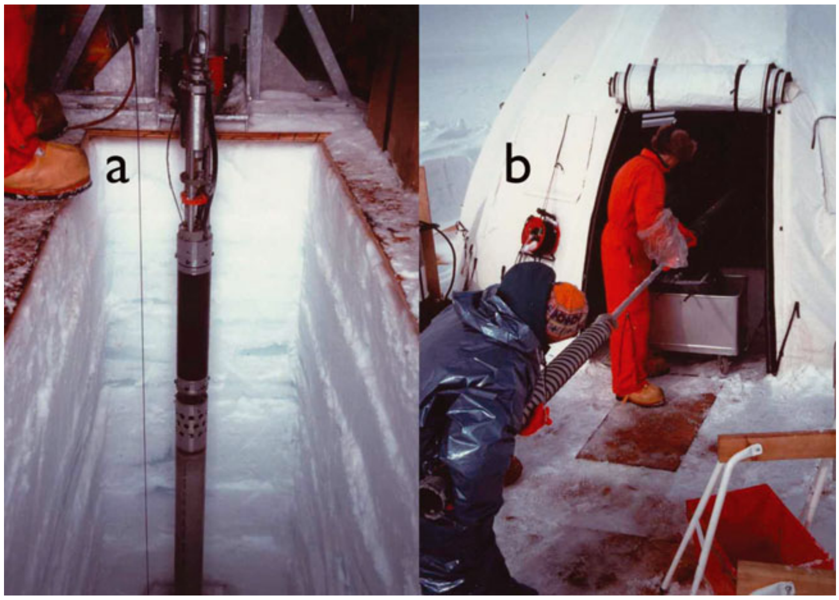


**Fig. 6.** Hans Tausen 1995 drill test. (a) The drill hangs in the drill pit from the shallow winch and tower unit. The base of the winch is seen at top, and the drill parts from top are anti-torque section, (short) motor section and top of chips chamber. (b) S.B.H and P.J. mount the core barrel and hollow shaft inside the drill. When this unit is pulled out, all the chips in the chips chamber will follow, with the top valve acting as piston. The rest of the drill is inside the white dome tent.

After the field season the drilling group decided on different measures to increase chip transport efficiency, such as stepping up the rotation rate from 60 rpm to 80 rpm and installing more efficient boosters. Another option, not considered feasible by the group at the time, was to build a pump to replace the booster, which in any case is not really pumping liquid but moving and compacting thick slush (as well as dry chips). In fact the spirals are mainly responsible for transporting the chips. Such a pump was, however, designed and built (Figs 3 and 7) by the UCPH group and installed in the drill for the NorthGRIP 1997 season. The pump is a double-action piston pump with two pistons, featuring six 30 mm diameter spring-loaded flap valves each, moving 2 cm in anti-phase inside a special sleeve fixed to the top of the grooved outer barrel (Fig. 7). The pump delivers a maximum 20 L min$^{-1}$ at 60 rpm rotation speed and allows the liquid to pass through it during descent of the drill. Another obvious advantage of the pump compared to the booster was the ability to keep all the chips inside the chips chamber even after aborted runs with only a half-full and unpacked chips chamber.

The pump immediately improved the performance of the drill and we again recovered long unbroken cores. The drilling was easy, but only just over 90% of the chips in each run were collected. This meant extra cleaning of the hole during night shifts. By going for shorter runs, 3.0–3.5 m or so, we would most likely have ensured full chip recovery as was later experienced by the EPICA Dome C drilling crew (Augustin and Antonelli, 2002). Ease of operation is another important feature of this drill system.

Two HT drills were built, one for the NorthGRIP project and one for the EPICA project (often referred to as the EPICA drill short version). A slightly longer HT-type drill with a 2.14 m long core barrel was also built for the Berkner Island (Antarctica) project (Mulvaney and others, 2007). That drill is also being used in the Italian Talos Dome (Antarctica) drilling project. Two pairs of long deep drills were made for the NorthGRIP and EPICA projects, with slightly different core-barrel/chips-chamber length ratios. The most recently built drills were given longer chips chambers in order to help recover more cuttings. Two of the deep drills were lost by being terminally stuck after hard packing around the drill head and a subsequent failed core break, while most of the short inner parts of the second EPICA deep drill were lost in transit from Dome C. The only remaining NorthGRIP deep drill was used to drill the EDML deep core. A new electronics package (without the batteries of the ISTUK drill) was designed and built for the NorthGRIP/EDML drill by the late N. Gundestrup, F. Wilhelms (F.W.) of the Alfred Wegener Institute, Germany, and S. Sheldon (S.S.) of the UCPH group. The HT drills were also used to deal with the warm ice encountered in both the EPICA and NorthGRIP projects due to their convenient length and easy handling. Without additional remedies the cores drilled close to bedrock were much too short. At NorthGRIP, EDC and EDML, drilling became possible again after a 'cognac bomb' (further discussed below) was installed in the chips chamber prior to each run. At EDML, novel modifications were made to the drill head and made the drilling faster. In 2006 the HT drill was used on Flade Isblink, northeast Greenland, for testing new drilling fluids. In the coming years it will also be used to recover new ice cores in Antarctica, on Roosevelt Island and in Aurora Basin. For the next deep drilling in Greenland (North Eemian) we will have to make changes to the NorthGRIP drill in order to cope with the higher viscosity of the new drilling liquids.

## PROBLEMS WITH DENSIFIERS

The drilling fluid normally used was D60 mixed with Frigen 141b as a densifier. This densifier has a most annoying property: it sticks to the fine chips and makes them sink to the bottom where they prevent the drilling fluid from mixing with the freshly cut chips, initiating hard packing around the

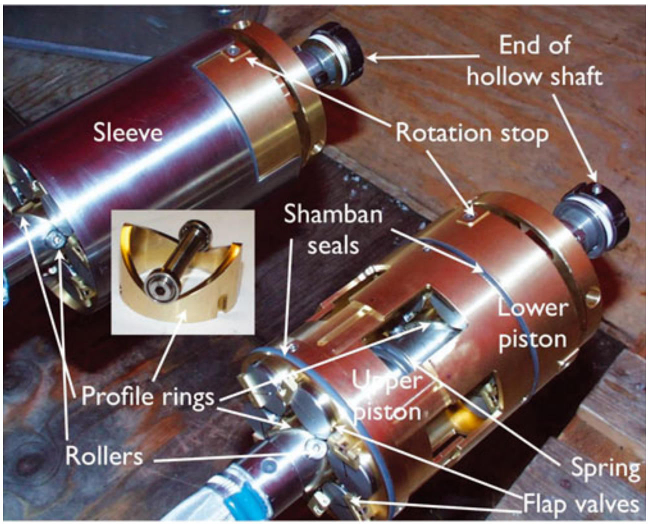


**Fig. 7.** Two pump assemblies mounted on the hollow shafts; one is inside the sleeve which normally is fixed to the top of the outer drill barrel. The fingers on the sleeve prevent the pump from rotating when the hollow shaft turns. The two wave-profiled rings on the shaft that are fixed onto the pistons are forced down (during 90° of rotation) by the rollers (replacing the initially used weak ball bearings), pressing the upper piston against a strong spring. The spring then moves the piston up (during the next 90° rotation) along with a volume of liquid. As the roller shafts are mounted at 90° and the profile rings are aligned in phase, the two pistons will move in anti-phase. Detail of the roller/wave profiled ring assembly is shown in the inset. In case of packed chips in or on top of the pump, no damage will come to the pump assembly, as the springs will just stay compressed. The circular flap valves ensure the liquid will move upwards as well as ensure free flow through the pump when descending in the hole.

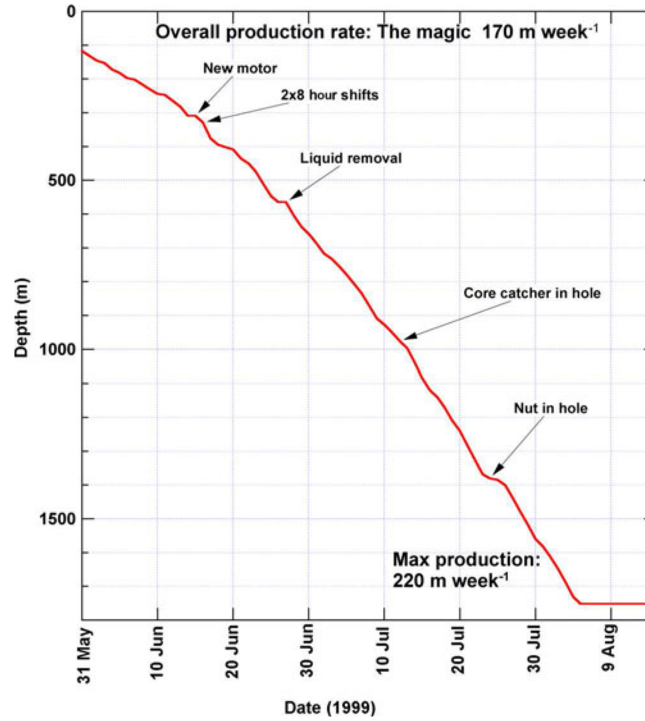


**Fig. 8.** The NorthGRIP 1999 record core production, 1630 m in one season. Experiments with a new and 'better' densifier, Sukane 123, had to be aborted, as the densifier was increasingly attached to the chips, with increasing pressure bringing them to the hole bottom and disrupting the drilling process. The new liquid had to be bailed out of the hole at 670 m depth and replaced with the regular Forane 141b densifier mixed in D60. Other problems with the drilling were more regular. Typical features of the production record are that the overall production is 170 m week$^{-1}$ during a drilling season and maximum production is found at the end of the drilling season when most encountered problems have been solved and the drilling crews fully trained.

drill head, a situation that can end with a stuck drill. With the pump installed it should be easy to clean the chips from the bottom by lowering the rotating drill slowly so the pump can suck in the chips before touchdown. Initially we planned on having both valves closed and the hollow shaft open while cutting the ice. This configuration works well during drilling but does not work well while cleaning the hole bottom. Cleaning requires the bottom end of the hollow shaft to be closed (e.g. with a spring-loaded ball valve) to prevent the liquid from moving down into the inner barrel and ensure that the circulating fluid goes up the hollow shaft and down the outside of the drill (where cleaning is most needed) and back to the drill head and pump. At the same time the lower valve must be kept open by replacing the upper disc with a ring in order to allow the liquid on top of the core to escape during drilling.

Unfortunately, slow feed-out was not possible with the available winch controller, and the only way to feed cable was to release the brake manually for the shortest possible time. Due to the static friction of the skates, this caused the drill to jump 5–10 cm when it finally moved. This intermittent method works well when drilling has started, but often fails to clean the hole bottom properly before cutting starts, as the drill must stop immediately above bottom after the final cleaning slack has been given, and this only happens by 'accident'. At NorthGRIP in 1997 these unsolved winch problems resulted in a stuck drill at 1372 m.

A new hole was started at NorthGRIP in 1998 using the dry version of the HT drill for drilling the access hole. The dry drilling was fast and stable and the hole was plumb to within a fraction of a degree. The much shorter UCPH shallow drill would normally end up with 2–3° inclination at 100 m.

The next stuck-drill situation came up in the year 2000 at 2930 m depth, fortunately in quite warm ice; recovery with (pure) ethylene glycol is quite easy. In EDC the drill got stuck twice in spite of a winch controller capable of slow feed. The second time at 786 m in the 1998/99 season resulted in a lost drill (Augustin and Antonelli, 2002). Due to the very cold temperatures, ethylene glycol would not have released the drill. Many runs were lost on this account, but the drillers could somewhat improve the situation by pulling the drill up fast from the bottom with the upper valve closed before starting to drill, in order to mix the bottom chips with more liquid. It was not until 2003 that we had access to a proper winch controller at NorthGRIP, which helped prevent drill sticking during the difficult warm-ice drilling in 2003 and 2004. In the 2001 season we actually had the drill stuck nearly ten times in the warm ice but fortunately it could be released by dumping a few frozen 100 g pellets of pure ethylene glycol in the hole. The pellets would melt in the warm, deep part of the hole and find their way to the hole bottom where they dissolved the packing at the drill head to release the drill.

Glycol was thus an important lifesaver for stuck drills. Having glycol in the hole could possibly have 'lubricated'

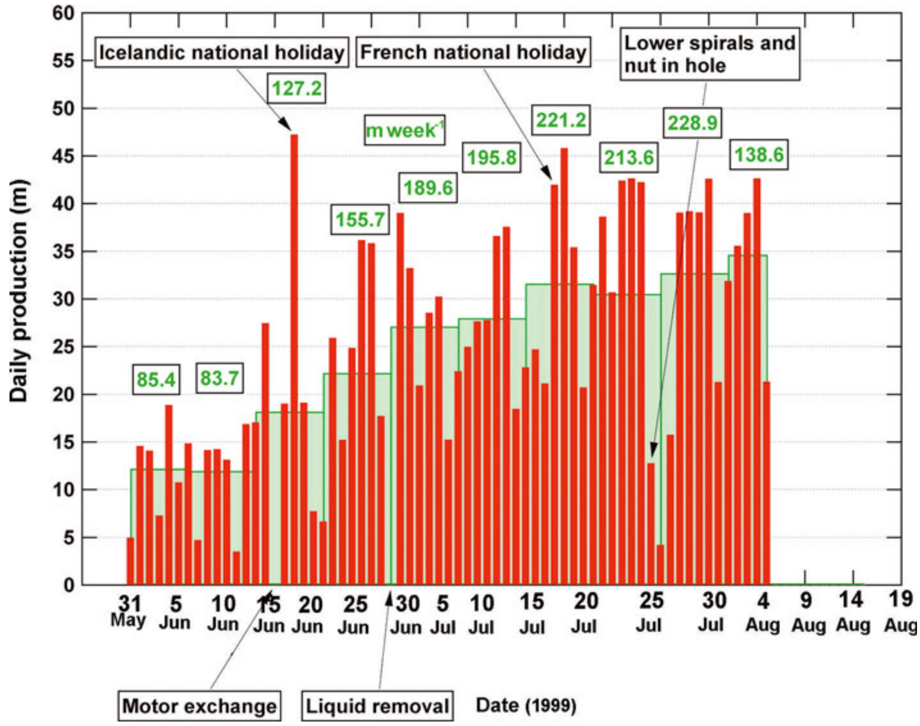


**Fig. 9.** Daily (red bars) and weekly (green boxed values) production at NorthGRIP 1999. The friendly national competition did not hurt the production rate.

the hole bottom for easier drilling, but eventually when the heavy glycol mixture had dissolved enough ice at the bottom it seemed to become light enough to start moving up into colder ice where it would start freezing out and building annoying glycol/ice bridges that blocked free passage of the drill in the hole (it is also possible that these bridges were leftovers from the 2000 season when an unknown amount of engine antifreeze was dumped in the hole to free the stuck drill).

## SPIRALS

The spirals were initially designed to fill the 4.5 mm wide clearance between the inner barrel and the inside of the grooved outer barrel for moving the chips upwards during drilling. This works well in dry drilling mode, but in wet drilling mode, with the pump installed, the chips/liquid mixture has to be sucked through the three independent channels between the three spirals; fundamentally a most unstable situation as was discovered during the 1997 drilling at NorthGRIP. Many runs were lost when one of the channels became blocked, resulting in packing at the drill head and an aborted run. The solution to the problem was to install thinner spirals. Initially we used 2 mm thick wires wound around the core barrel. This worked well, as now there was only one channel leading to the pump and the wires helped stir up the chip/liquid mixture, preventing coagulation of the chips and blocking of the flow. Before installing the wires, an experiment was made to run without any spirals on the core barrel. This failed utterly. Subsequently, the wires were replaced by 2 mm thick, 10 mm wide aluminium strips. Another experiment, insisted upon by one of the trainees, was to have the strips end at the centring knobs 10 cm above the lower end of the inner barrel. In this short interval where the strips were missing, the chips separated from the mixture, resulting in blocked chips transport and immediate packing. The lesson learned was that the chip/liquid mixture needs to be well stirred at all times.

After final tuning of the drill, the 1999 NorthGRIP drilling season produced a record high 1630 m of good core (Figs 8 and 9). Drilling problems were a little more tricky than expected, but our overall mean core production rate was 170 m week$^{-1}$.

## THE BAYONET COUPLING

The constant threat of a stuck drill in the NorthGRIP drilling project inspired the UCPH group to design a special coupling between the drill and core barrel as shown in Figures 3 and 10. The aim was twofold. First, in a stuck-drill situation, it would make it possible to leave only the core barrel in the hole if all rescue efforts were in vain. Secondly, the coupling could allow an efficient hammer to release the drill when stuck. This feature, however, needs to be further developed. When the NorthGRIP drill got stuck in 2002 we were not able to release the core barrel, as the friction in the rollers was too high and the shear pin in the gear shaft broke. This pin is a leftover from the ISTUK drill, made necessary by the piston-moving screw, but is not needed in the HT-type drills. To use the super-banger/hammer feature of the coupling requires that the electronics can withstand very high g-forces.

## WARM-ICE DRILLING

Observations made during the GRIP drilling project (Johnsen and others, 1994) showed the formation of refrozen water on the cutters at ice temperatures of –10°C or even colder. The problem did not occur at Dye 3, Greenland, where the

**Fig. 10.** Bayonet coupling or the super banger. The upper block is attached to the lower end of the hollow shaft, and the sleeve is welded to the top of the core barrel. The three rollers on the block can be latched on, inside the grooves of the sleeve. This way the core barrel can be mounted on or released from the drill at the bottom of the hole or at surface. Another feature can provide heavy impact on the core barrel by pulling hard on the drill with the rollers in the lower left (normal) position and then rotating the drill backwards. This feature still needs to be properly tested but could help to release stuck drills as the main mass of the drill is acting as a hammer.

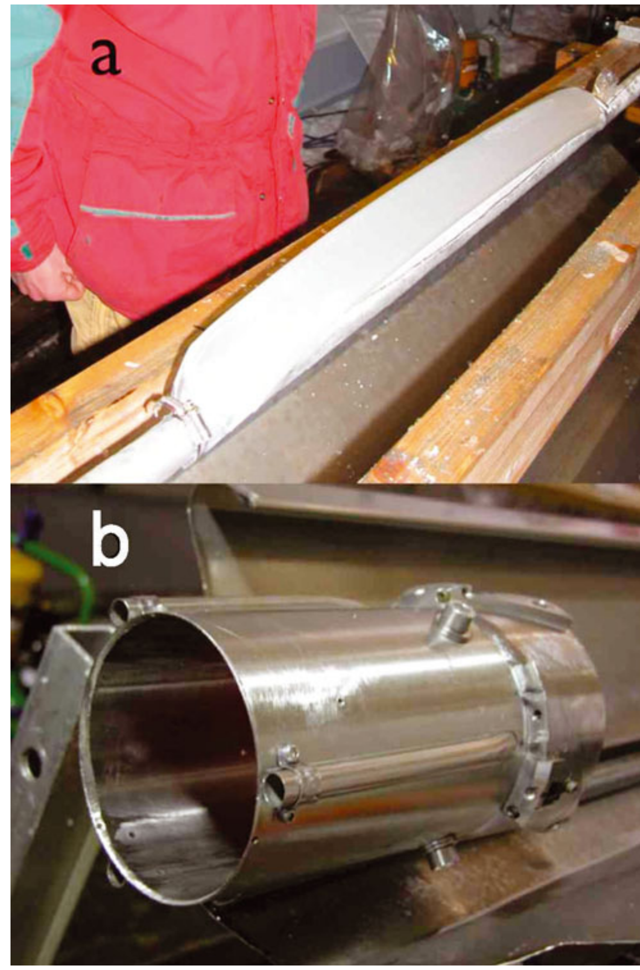


**Fig. 11.** (a) The 'cognac bomb', a 0.5 L plastic hose filled with 50% EWS attached to the hollow shaft with hose clamps. When the motor starts, the hose is ripped open by a removable screw in the chips-chamber wall and the ethanol mixture is circulated down to the drill head, preventing refreezing of meltwater. (b) Before drilling became stable, some non-magnetic nuts and screws had to be removed from the bottom of the hole. This was done using a most efficient vacuum cleaner designed and built by A.Z. It is attached to the drill head, and the pump sucks liquid through the pipes when the drill rotates.

basal temperature is –13°C (Gundestrup and others, 1984); however, at GRIP, as the ice temperature became warmer, up to the maximum of –8.5°C at the bottom (Johnsen and others, 1995), the cutters produced a great amount of refrozen melt that would frequently build a bridge between the cutters and channels, blocking the chip transport, producing packing and a short or lost run. Drilling in warm ice thus became a real challenge for the NorthGRIP and EPICA drilling projects, as the bottom temperatures at NorthGRIP, Dome C and DML turned out to be at the pressure-melting point, ~–2.4°C.

The problem was first encountered at NorthGRIP during the 2002 season. We had some ethylene glycol in the hole but it did not seem to ease the meltwater problem (although it certainly helped to release the drill every time it got stuck). Another problem was the sticking of the core in the core barrel due to freezing of the glycol mixture (and later the ethanol mixture) between the core and core barrel during pull-up. The solution was to first heat the entire drill inside a long box with warm air from a Hermann–Nelson blower and, when the core barrel was released, to heat the barrel in a D60 bath to a temperature close to the actual temperature during drilling.

The warm ice became difficult to drill at Dome C in the following, 2002/03, drilling season (Augustin and others, 2007). The drilling group had recommended that ethanol be brought to Dome C to help cope with the meltwater and subsequent freezing on the drill and core. This turned out to be a most difficult venture as, although the ethanol water solution (EWS), brought to the bottom of the hole, initially helped the drilling, most of the EWS unexpectedly turned into great amounts of ice–ethanol slush obstructing the drilling until it was cleaned out.

At NorthGRIP the warm-ice problem was first seriously attacked in the 2003 season. We brought a heated isolated tank to bring EWS to the bottom and we also brought an ethanol thermal drill (Zagorodnov and others, 2002). We hoped the thermal drill would be ideal for drilling in ice close to the pressure-melting point. Our initial experiments resulted in the following outcome. Firstly, the ethanol brought down to the bottom in the tank behaved much worse than we had expected, eventually turning into slush, inhibiting further proper drilling. Secondly, the spiral heater at the lower end of the thermal drill burned out as soon as the drill touched bottom, most likely due to extremely high voltage (in the megavolt range) between the NorthGRIP camp and the (pink electrolytic) water in the ice matrix in galvanic contact to bedrock.

**Fig. 12.** The NorthGRIP 2003 drillers. Back row (left to right): J. Schwander, S.J. Johnsen and H. Motoyama; front row (left to right): T. Popp, V. Zagorodnov and L. Augustin. Most of the drilling difficulties were over with the 'cognac bomb', as witnessed by the facial expressions.

## THE 'COGNAC BOMB'

Based on the difficulties experienced so far with using EWS to deal with the warm ice, it was decided to deliver only a limited volume, around 0.5–1 L, of about 50% EWS with the drill in each run. The aim was to drill enough core during the run to recover most of the EWS brought down in the chips chamber to prevent excessive formation of slush. The EWS was stored in a 5 cm diameter, 0.5 L, plastic hose, the 'cognac bomb' closed with two knobs and clamped to the hollow shaft of the HT drill with hose clamps (Fig. 11a). When the drill motor was started, the plastic hose was ripped open just above bottom by a pointed screw extending through the wall of the chips chamber. The pump would then ensure that the released EWS would circulate down to the drill head and prevent or slow down refreezing of the meltwater produced by the cutters. The drilling, however, did not become stable until some non-magnetic nuts and screws had been removed from the bottom of the hole using a newly built vacuum cleaner (Fig. 11b). The 'cognac bomb' worked much better than earlier experiments with EWS, and the drillers became much happier, as Figure 12 clearly indicates. We were able to drill up to 5 m of good core daily down to 3085 m depth, when the bottom meltwater flushed the hole, immersed the drill and shorted the electric connections in the anti-torque section.

In 2004 the drilling was continued in order to recover the 45 m of refrozen bottom water from the previous year. By using the same ethanol procedure as in the previous year and the same winch controller, the drilling went on in a stable routine and bedrock was reached at 3090.5 m, 5.5 m below the water channel we drilled into the year before.

## THE ULTIMATE LESSON LEARNED

During decades of drilling in polar ice, one lesson we have learned stands out as being the most important. It often happens that a mistake is made or something goes wrong with the mechanics or the electronics. The operator will then quite often be tempted to play the hero and go for a quick fix of the apparent problem. He may be lucky and all goes well, but more often, by not having analyzed the event thoroughly in an open discussion with those who know the system, he will misunderstand the situation and make a wrong decision. Such decisions will frequently produce damage an order of magnitude worse than if a decision had been made based on a sound understanding of the problem. The scenario is like the second-impact damage in a car accident. When bad things happen (and they will), take a break and discuss the problem in the open before any action is taken.

## ACKNOWLEDGEMENTS

We are greatly indebted to the various funding agencies for supporting the projects involved, including the cost of drill development and drilling. We also thank all the logistic people for organizing the field camps and for bringing us there along with our equipment. The numerous drillers who put long cold hours into careful drilling and recovery of good-quality cores are thanked for their vital contribution, and for helping to improve the drills and drilling techniques. Finally we thank the scientific teams for making such good use of the ice cores we managed to deliver. To drill good ice cores against all odds is a most satisfying experience in a well-functioning drilling camp, but to see the final outcome described in high-level scientific papers should also be a fully acceptable reward.

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# The Berkner Island (Antarctica) ice-core drilling project

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**ABSTRACT. We describe a project to retrieve a 948 m deep ice core from Berkner Island, Antarctica. Using relatively lightweight logistics and a small team, the drilling operation over three austral summer seasons used electromechanical drilling technology, described in detail, from a covered shallow pit and a fluid-filled borehole. A basal temperature well below pressure-melting point meant that no drilling problems were encountered when approaching the bed and the borehole penetrated through to the base of the ice sheet, and sediment was retrieved from beneath the ice.**

## INTRODUCTION

Lying to the south of the Weddell Sea, embedded between the Ronne and Filchner Ice Shelves, Berkner Island is the largest Antarctic island (Fig. 1). Roughly kidney-shaped (Fig. 2), it rises to two domes approximately 140 km apart: Reinwarthhöhe in the north at 720 m a.s.l., and Thyssenhöhe in the south at 890 m a.s.l., separated by a trough, the McCarthy Inlet. The island has no rock outcrops, and an almost ideal topography for ice-core drilling, with shallow slopes leading to the domes and relatively flat bedrock a little below sea level over much of its base. The first shallow firn cores (to 11 m depth) were drilled on the north and south domes of the island in 1990 (Wagenbach and others, 1994). Clear seasonal cycles in both the stable isotopes and some chemical species were evident, and it was noted at the time that these two domes appeared to provide ideal sites for longer-term climate records. Deeper cores were recovered in the 1994/95 season, achieving depths of 151 m on the northern dome (by the British Antarctic Survey (BAS)) and 181 m on the southern dome (by the Alfred-Wegener-Institut für Polar und Meeresforschung (AWI)) using two shallow electromechanical ice-core drills. Mulvaney and others (2002a) describe the drill used by BAS on the northern dome, which was a development of the AWI shallow drill used on the southern dome, itself based on earlier Swiss designs (Rufli and others, 1976; Schwander and Rufli, 1988). Isotopic and chemical records from these ice cores (Mulvaney and others, 2002b) spanned 700 years for the shorter north dome core, while the 181 m deep core from the southern dome represented approximately 1200 years. Both cores display clear seasonal cycles in electrical conductivity measurements, allowing dating by annual-layer counting and the calculation of accumulation profiles. Stable-isotope measurements (both $\delta^{18}O$ and $\delta D$), together with the accumulation data, showed multi-decadal variability around a generally stable long-term mean over the past millennium. The 10 m temperature at the northern dome was measured as –24.1°C, while the higher southern dome was measured as –26.1°C, with accumulation rates of 210 and 130 kg m$^{-2}$ a$^{-1}$. Mulvaney and others (2002b) suggested that the southern dome would be an ideal site to gain a climate history of the late stages of the last glacial period and the deglaciation for comparison with the records from the deep Antarctic ice cores, and with other intermediate-depth cores such as Law Dome, Taylor Dome and Siple Dome.

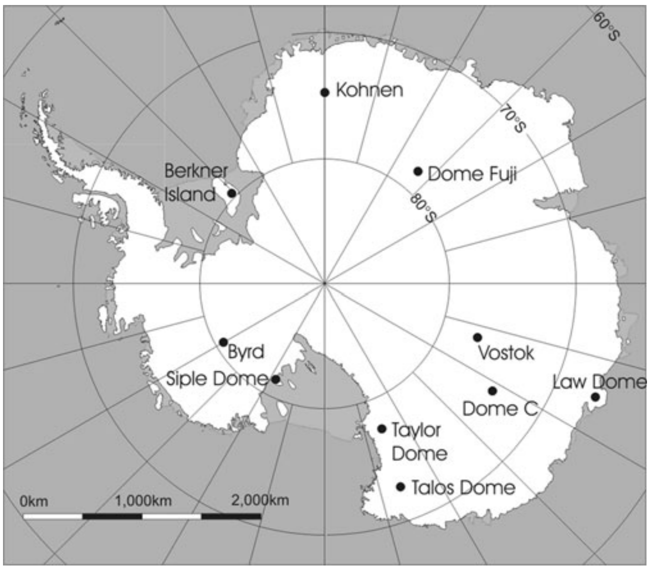


**Fig. 1.** Location of Berkner Island and other deep ice-core drilling sites in Antarctica.

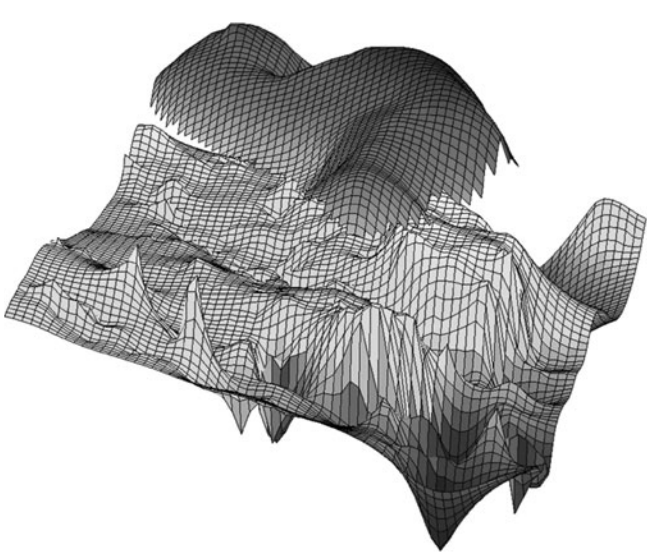

**Fig. 2.** Surface and bedrock topography of Berkner Island.

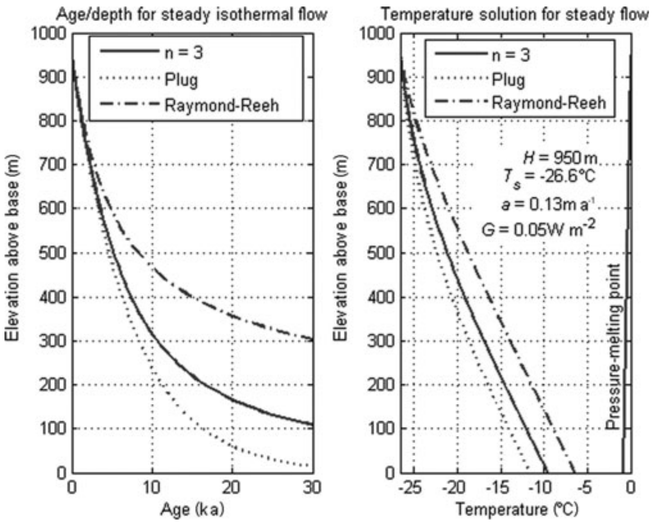


**Fig. 3.** Model estimates of the depth–age relationship assuming steady isothermal flow (personal communication from R. Hindmarsh, 1999). Three flow-law models are tested, using a column thickness of 950 m, an accumulation rate of 130 kg m$^{-2}$ a$^{-1}$, a surface mean temperature of –26.6°C and a geothermal heat flux of 50 mW m$^{-1}$.

**Table 1.** Drill site location and physical characteristics

| | |
|---|---|
| Latitude | 79°32.9′ S |
| Longitude | 45°40.7′ W |
| Altitude | 890 m a.s.l. |
| Ice thickness | 947 ± 1 m |
| Accumulation | 130 kg m$^{-2}$ a$^{-1}$ |
| 10 m temperature | –26.5°C |
| Basal temperature | –11.6°C |

Airborne radio-echo sounding measurements through the ice cap (Sandhäger, 1996) indicated a relatively flat and horizontal bed in the vicinity of the south dome and a thickness of around 950 m. Over-snow radar measurements (Steinhage and Blindow, 1996) showed a near-perfect stratigraphic column (evidenced by the clear internal layers in the radar reflection profiles) through most of the ice thickness, and no evidence of distortion in the layers that might indicate ice flow, or any likely discontinuity in the age–depth profile. From common-midpoint measurements, they gave the thickness as 947 ± 1 m.

Model estimates of the depth–age relationship (Fig. 3) assuming steady isothermal flow (personal communication from R. Hindmarsh, 1999) predicted that the transition would be at about 250 m above the bed, with a potential age of more than 30 ka near the bed. This simple model assumed steady isothermal flow based on a column thickness of 950 m, an accumulation rate of 130 kg m$^{-2}$ a$^{-1}$ and a surface mean temperature of –26.6°C. Since no account was taken of lower accumulation in the glacial period, it was reasonable to assume that the ultimate basal age might be considerably older than 30 ka. Further, the model predicted a basal temperature of around –10 to –12°C, using an estimated geothermal heat flux of 50 mW m$^{-2}$. This basal temperature is well below the pressure-melting point of ice, encouraging for any deep drilling operation: drilling would be unlikely to suffer the problems associated with penetrating near-melting ice.

## MOTIVATION FOR THE BERKNER ISLAND DEEP DRILLING PROJECT

1. Climate change at inland Antarctic sites (Byrd, Vostok) appears to be out-of-phase with Greenland: for example, the Antarctic Cold Reversal (ACR) precedes the Younger Dryas (YD) in Greenland (Sowers and Bender, 1995; Blunier and others, 1997). Recent results from the EPICA (European Project for Ice Coring in Antarctica) Dronning Maud Land deep ice core (EPICA Community Members, 2006) show a coupling between all Antarctic warm events and Greenland Dansgaard–Oeschger events during the last glacial period, with the Antarctic warming preceding that of Greenland. However, earlier results reported from Taylor Dome, a near-coastal site in East Antarctica, appeared to cast doubt on this simple pattern, suggesting that at this site the timing of the deglaciation was broadly in phase with Greenland, rather than central Antarctica (Steig and others, 1998). This apparent discontinuity with central Antarctic records poses severe tests on existing models of climate change, which have focused on the role of the Atlantic circulation in transferring heat between the hemispheres (Stocker and Johnsen, 2003) and have generally sought to explain the phasing of Northern/Southern Hemisphere link assuming each polar region responds coherently. Although the detail of the timing of the deglaciation of the Taylor Dome core has been questioned (Mulvaney and others, 2000), at the inception of the project a new climate record of the deglaciation period from a coastal site facing the southern Atlantic Ocean seemed an obvious choice for gaining further insight into the spatial pattern of the phasing.

2. Berkner Island is embedded within the Ronne and Filchner Ice Shelves. To the north of the island lies the Weddell Sea; Berkner ice flows directly into the Weddell on its northern coast. To the east of the island lies a deep bathymetric trench, the Thiel Trough, which reaches depths of 1250 m, while to the west and south further deep troughs reach depths of 750–1400 m. Thus, ocean water is able to flow around the whole of the raised bedrock below Berkner. Melting of the lower surface of the Filchner–Ronne provides a significant outflow of ice-shelf water, which is a contributor to the deep Antarctic Bottom Water (AABW) entering the Atlantic Ocean circulation system (Foldvik and others, 1985). While the exact flux of AABW from the Weddell Sea has proven hard to quantify in the context of experimental uncertainties and variability on different timescales, it is universally accepted that this is the major source region for this water mass (e.g. Jacobs, 2004). At the Last Glacial Maximum (LGM), shelf ice is likely to have reached further northwards in the Weddell Sea, probably to the continental-shelf break (e.g. Huybrechts, 2002). The position of the ice-shelf front is likely to have had an impact on the production and outflow of AABW, and with it, perhaps, an influence on the global climate (Broecker, 1998). Knowledge of the evolving climate of this source region for cold AABW since the LGM, and the extent of the ice sheet, and the timing of its withdrawal from the continental-shelf break seems highly relevant to


**Fig. 4.** (a) General view of camp. (b) The drilling tent after two winters of accumulation.

the modelling of the palaeo-ocean circulation system. The Berkner Island ice cap is probably the best site in the Antarctic Peninsula/Weddell Sea region for obtaining a high-resolution climate record for the period from the LGM through to the Holocene.

3. Several models of the extent and thickness of the Antarctic ice sheet through the last glacial cycle indicate that the Antarctic ice sheet extended out into, and filled, the Weddell and Ross Sea embayments. In the Weddell Sea, the ice may have reached the continental-shelf break approximately 450 km north of Berkner Island, with an ice thickness of up to 2500–3000 m (e.g. Ritz and others, 2001; Huybrechts, 2002). The volume of ice in the Weddell Sea at the LGM could be equivalent to as much as 3–5 m of sea-level reduction during the late glacial period. The timing of the retreat occurs quite late in some models, with Berkner Island not appearing as an independent ice cap until late in the Holocene at around 4 ka BP (e.g. Huybrechts, 2002). With ice as thick as this, there is the question of the extent of the ice flow across Berkner Island, and whether there was sliding at the base. Gross flow across Berkner Island, and advection of ice from a possible higher-altitude, inland source, clearly poses some difficulties in interpreting any climate record from a deep ice core. However, it was clear that a core from this location would provide some answers to the pertinent glaciological questions of ice thickness and volume in the Weddell Sea at the LGM, the timing of the retreat of the ice and the point at which Berkner Island became an independent ice cap.

## PROJECT LOGISTICS

The location and main physical characteristics of the chosen drilling site are detailed in Table 1. The primary constraint on the logistics for the drilling project, and a limit to the size and capacity of the drilling system, was the access to the drill site. The UK Antarctic logistic operation (BAS) consists of two ice-strengthened ships for support of the UK Antarctic research stations, four de Havilland ski-equipped Twin Otter aircraft, and one de Havilland Dash-7 four-engined aircraft. The Dash-7 provides a transcontinental link between a gravel runway at Rothera Station on Adelaide Island and South America or the Falkland Islands, together with a link to a blue-ice runway (Sky Blu) in the south of Palmer Land. Field operations remote from the two main Antarctic stations (Rothera on Adelaide Island to the west of the Antarctic Peninsula, and Halley on the Brunt Ice Shelf to the east of the Weddell Sea) are all air-supported by the Twin Otter aircraft, with logistic staging posts at Fossil Bluff (eastern Alexander Island) and Sky Blu. BAS has no capacity for mounting a large over-snow cargo traverse, with the only over-snow cargo vehicles operating to relieve Halley Station, transferring cargo between ships moored alongside the ice shelf and the station. Thus all the drilling and camp infrastructure, fuel, cargo and personnel had to be moved to the drill site by Twin Otter. In practice, most of the heavy cargo was shipped to Halley and transferred to Berkner, a distance of around 900 km. This could be accomplished usually via a direct flight from Halley, with refuelling at the drill site for the return leg. Personnel flew via Dash-7 from the Falkland Islands to Rothera, and then out to the drill site via Twin Otter, a direct distance in excess of 1200 km, with refuelling at Fossil Bluff, Sky Blu and other fuel depots as required by weather or operational constraints. All ice cores were flown to Halley, and loaded into a –20°C refrigerated container on the support ship for return to the UK.

The constraint on transport led to the need for a new drilling system (described later) designed to fit the final Twin Otter leg of the supply chain. It also put limitations on the size of the drilling team, and the type of accommodation.

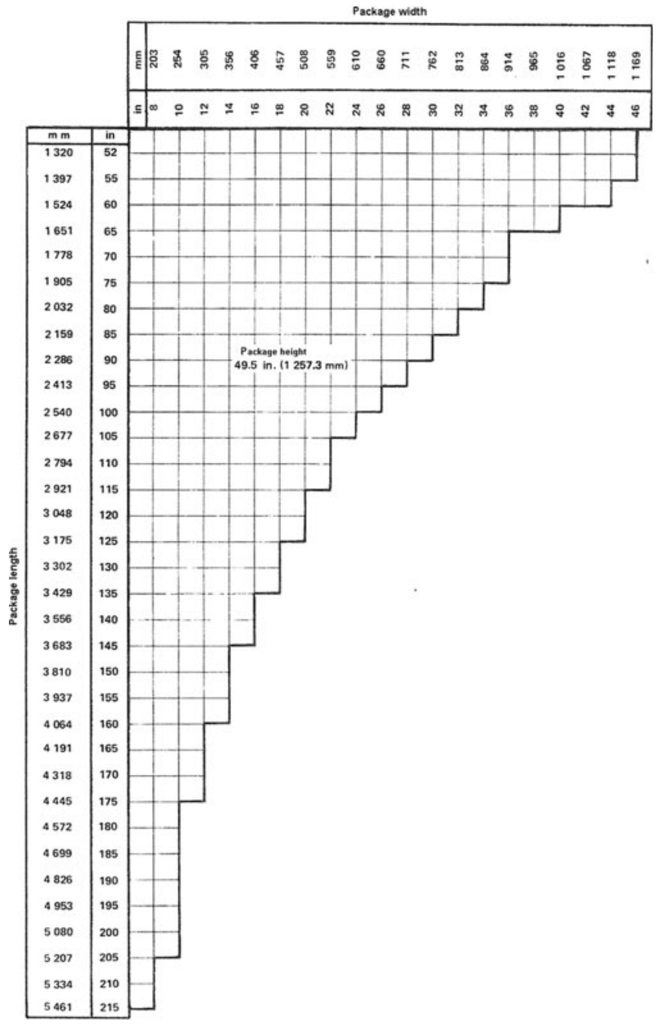


**Fig. 5.** Loading-width/length restrictions for the de Havilland Series 300 Twin Otter (in = inches).

The field team was limited to a maximum of eight, including drillers, scientists and all support personnel. In fact, the first season (setting up the drilling infrastructure, pilot borehole, reaming and casing) was accomplished by six people in total, the two main drilling seasons (drilling from pilot hole to the base) by just eight people, while the final season (logging the borehole, recovery of the basal sediment and uplift of all infrastructure) required four people at the site. In each season, personnel included a field leader, drillers, scientists and a person primarily responsible for safety and logistics in the field: all drilling and camp-related work, including cooking, was shared between all those in the field. In common with the BAS field procedure, sleeping accommodation was two-person pyramid tents. A larger Weatherhaven Polarhaven shelter (7.3 × 3.7 m) was provided for messing and relaxation, a Weatherhaven Series 4 shelter (8.5 × 4.3 m) for engineering support, and a further Weatherhaven Series 4 (14.6 × 4.3 m) to cover the drilling pit (Figure 4 gives an impression of the drilling camp). Rudimentary toilets and showers were provided using pyramid tents, while a small shelter was used to house the main camp generator. Only the Weatherhaven covering the drilling trench was left erected over the winter season when the site was unoccupied, and it suffered some structural damage due to burial by snowdrift.

**Fig. 6.** Unloading the winch frame from the Twin Otter using H-section ramps.

## THE BERKNER ISLAND DRILLING SYSTEM DESIGN

Drawing on the experience gained from the EPICA drilling project (Augustin and Antonelli, 2002), a new drilling system was designed by the Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) with BAS and the Institut National des Sciences de l'Univers (INSU, France) Technical Division in order to fit the specific constraints of the Twin Otter transport route. The main constraints on the design were maximum load carried by Twin Otter (up to around 900 kg, depending on fuel load and operational factors), overall dimensions of the cargo door (1.42 m high × 1.27 m wide) and the length/width restrictions of loading a Twin Otter (Fig. 5). As an example, the latter constraint dictated the largest possible outer barrel tube length of 5.4 m, which ultimately restricted the maximum core length possible to 2.05 m. As another example, the restriction on the size of the cargo door governed the choice of main generator, and ultimately the maximum motor power, and therefore the speed and maximum pull of the drilling winch. A secondary consideration in the design of the system was handling in the field: although heavy lifting equipment was available on the stations to load the aircraft, once at the drilling site no lifting equipment was available, and all equipment needed to be capable of being handled over snow, by the use of manpower, or skidoo and sledge. BAS operations use two lightweight H-beam ramps to assist in loading and unloading heavy equipment in the field. Figure 6 shows an example of aircraft cargo handling.

### The winch and mast

The winch-system (Fig. 7) detailed design and manufacture was subcontracted to the Danish company MacArtney A/S. It was designed and built specifically for this project in collaboration with LGGE and BAS in order to fit into a Twin Otter and to meet the technical specification for drilling in ice. The motor, the gear-reducer and the mast and mast tilt mechanism could easily be dismounted from the main frame to help manhandling in the field. The winch frame is made of square stainless-steel profile (50 × 50 × 5 mm). Its overall dimensions are 1200 mm long, 1100 mm wide and 1080 mm high. The Lebus drum capacity is 1100 m of 8.4 mm diameter cable in 19 layers; a level-wind system managed the cable feed onto the drum. The winch is powered by a VEM 9 kW (3 × 400 V, 50 Hz) electric motor with a Wistro K21R cooler,

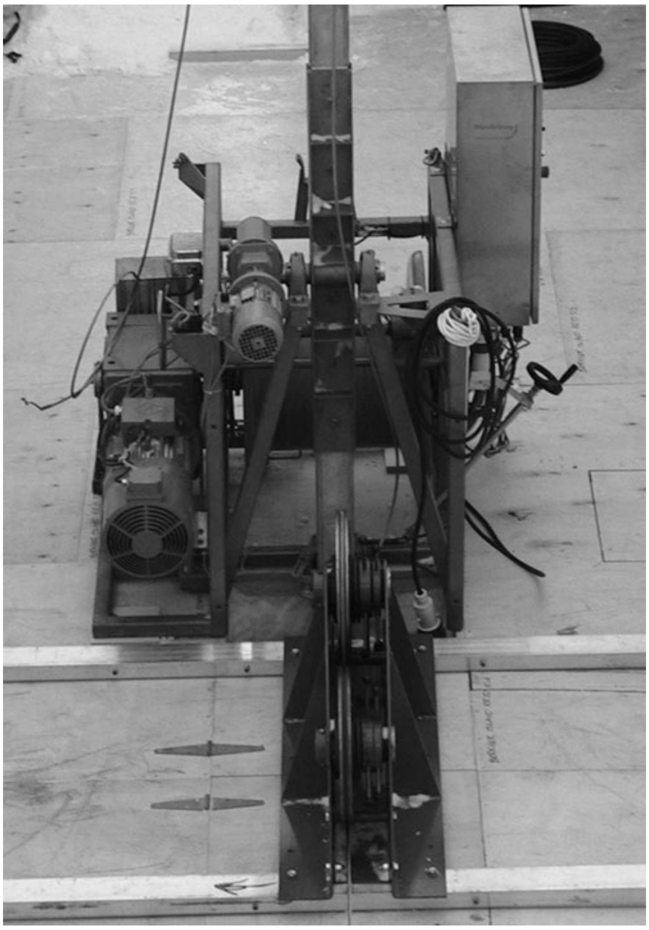

**Fig. 7.** The winch and mast system with cable-tensioning device in the foreground, ready to roll cable onto Lebus drum, visible at the rear of the frame. On the left of the winch frame is the motor and gear reducer; on the right is the handle for engaging the locking mechanism for the mast in the upright position and the winch control panel; in the top centre of the frame is the mast tilt mechanism with its gear motor.

driving through a Tramec TC 160C gear reducer (reduction ratio $I = 80{:}1$). The gearbox includes the facility to attach a handle for manual winding to recover the drill in the event of an electrical systems failure. The motor is driven by an Omron 3G3MV-A frequency inverter associated with an absolute encoder set up on the winch motor. This system allowed a cable winding speed ranging from 0.3 to 43 m min$^{-1}$, and a maximum pull of 15 kN on the first cable layer, reducing to 10.5 kN on the top layer. A Mayr 104 V electric parking brake on the winch motor linked to the motor drive prevented cable run-out, and could be disengaged for drilling. To slow the winch speed during drill descent, the motor can be switched to a generator mode, and the power dumped across a resistive load. A stainless-steel mast of welded box-section construction, 100 mm square and of overall length 7.4 m, split in the middle for transport, was mounted on an axis at the upper front of the frame, and topped with a nylon sheave wheel 0.45 m in diameter. The mast could be tilted from the vertical to the horizontal for unloading the core and chippings either manually or via an electric motor-driven tilting system. Once in the vertical drilling position, it was clamped using manually closed claws, with a safety cut-out to prevent winching with the mast unsecured. The winch system weighed 850 kg overall (without cable), and this could be broken down into components that could be transported and assembled in the field without machinery: winch frame 420 kg, motor 85 kg, gear reducer 150 kg, mast system 100 kg, pivoting axis system 65 kg and control box 30 kg.

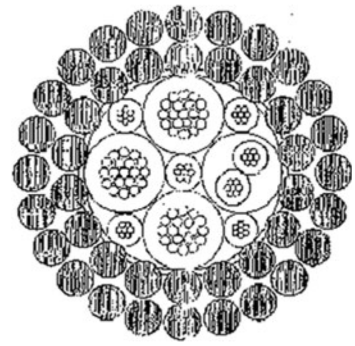

**Fig. 8.** Cross-section of the drill cable.

### The cable

The cable is manufactured by Schlumberger. It comprises eight conductors plus a twisted pair (for a total of ten conductors) in an armoured outer cable with an overall diameter of 8.4 mm (Fig. 8). The armour wires are high-tensile, galvanized improved plough steel. The breaking strength of this cable is 38.8 kN while the elastic limit is estimated around 25 kN. Cable weight was 280 kg km$^{-1}$, and approximately 1100 m of cable was loaded onto the winch (totalling 308 kg). The larger-diameter conductors were used to transmit power to the drill motor; each had a resistance of 21 $\Omega$ km$^{-1}$, while the smaller-diameter conductors were used for transmission of analogue sensor signals from the drill pressure tube.

## THE DRILL

LGGE built a new drill modified to the logistic constraints of the Berkner project (particularly a shortened barrel, with limited electronics). The lower part of the drill draws heavily on the designs of the EPICA drill, and the earlier Hans Tausen drill (Johnsen and others, 2007), with a motor driving the rotation of a hollow shaft, a volumetric pump and a core barrel inside a fixed outer tube; the drill head was fixed on the inner rotating core barrel. A series of 24 grooves were machined on the inside of the outer tube, and three aluminium spirals were mounted on the core barrel in order to improve the chips/drilling-fluid transportation from the bottom of the drill to the chip chamber. The dimensions of the sections of the drill are given in Table 2. The pump used in this Berkner drill is the 'double piston pump' designed in Copenhagen University for the EPICA drill (personal communication from N. Gundestrup, S.J Johnsen and S.B. Hansen, 2000). Most mechanical components of this drill are made in stainless steel (304 L and 316 L), while the anti-torque skates are spring steel, and the pump body brass.

The motor/gear section incorporates a 190 V permanent magnet d.c. motor (TEM MP66 KL 190 V 2000 T, with a gear reduction of 24 : 1) producing 600 W for a duration of 15 min at 2000 rpm, with a continuous stall torque of 2.1 Nm (peak stall torque 10 Nm). The reduction ratio gave a drill-head rotation speed of 10–80 rpm. The electrical loss on the cable line is typically close to 50 V, the motor being

**Table 2.** Berkner Island electromechanical drill characteristics. OD: outer diameter; ID: inner diameter

| | |
|---|---|
| *Drill head* | |
| CUTTERS | |
| Number | 3 |
| OD | 129.6 mm |
| ID | 98.0 mm |
| Face angle | 45° |
| Clearance angle | 12° |
| CORE DOGS | |
| Number | 3 |
| OD on core dogs | 125 mm |
| BODY | |
| OD | 118 mm |
| ID | 99 mm |
| *Outer core barrel* | |
| OD | 118 mm |
| ID | 113 mm |
| Overall length | 5.4 m |
| *Inner core barrel* | |
| OD | 104 mm |
| ID | 100 mm |
| Length | 2.138 m |
| Rotation speed | 40–80 rpm |
| *Hollow shaft* | |
| OD | 30 mm |
| ID | 20 mm |
| Length | 3.2 m |
| *Pump* | |
| Type | Double piston (6 valves per piston), EPICA type |
| Stroke length | 15 mm |
| *Chip chamber* | |
| OD | 114.3 mm |
| ID | 110.3 mm |
| Length | 3.213 m |
| *Pressure tube* | |
| OD | 114.3 mm |
| ID | 98 mm |
| Length | 0.8 m |
| Pressure tight | 30 MPa |
| *Motor* | |
| Type | TEM MP66 KL (DC, permanent magnet) |
| Voltage | 190 V |
| Power | 600 W |
| Rotation speed | 2000 rpm |
| Moment | 2.1 Nm |
| *Gear-reducer* | |
| Ratio | 1:24 |
| *Anti-torque section* | |
| Type | 3 leaf springs, ISTUK type |
| Length | 960 mm |
| **Overall length** | **7.2 m** |
| **Overall weight** | **160 kg** |

driven at around 110–120 V (160 V at surface) with a current starting of 1 A at the beginning of a run, reaching 2.5 A at the end of a run. To enable a simpler operation in the field, there is no 'electronics section' in the pressure tube of this drill, such as found in the EPICA drill. There is only analogue signal transmission between the drill and surface (limited to detection of anti-torque rotation, load on the drill head and tachymeter) with the 8 + 2 conductors plus armour cable contacts passed through a 12-channel slip ring (Focal, type 180/12) in the Lebus drum axle.

The anti-torque section uses spring-steel flat skates, in common with most deep ice-core drills (Gundestrup and others, 1984). The link between the drill and the cable was made by potting the splayed cable in a low-melting-temperature expansive metal alloy (trade name Cerromatrix).

## Drilling-fluid system

In common with other recent European ice-core drilling operations, the Berkner project used a mixture of ExxonMobil 'Exxsol' dearomatized hydrocarbon solvent and HCFC-141b to achieve a fluid of the optimum density, and other physical characteristics (Talalay and Gundestrup, 2002). For this project, Exxsol D-60 was chosen as the base drilling fluid, with a density of 0.790 Mg m$^{-3}$ at 15°C, and 75 × 205 L drums (15 375 L) were delivered to the drill site. The densifier used was HCFC-141b, with the trade name Solkane and density 1.240 Mg m$^{-3}$ at 25°C, and 4096 L (5080 kg fluid) of densifier were delivered to the site in drums. Mixing of the fluid was carried out in an open 205 L drum, optimizing the density for achieving a slight over-pressure in the borehole with a fluid column height maintained at 80–100 m from the surface (the casing reached 67 m from the surface, and the pore close-off depth was 64 m). Fluid was made in batches of ~180 L, using the actual fluid temperature as delivered from the surface-stored drums and a pre-calculated chart to specify the density required at the surface to achieve the correct in situ density in the borehole (which varied in temperature from around –26°C near the surface, to –11°C at the base), and mixed using an electric paint-stirrer and narrow-range glass bulb hydrometers. Generally, the density of the mixture at the surface was about 946 Mg m$^{-3}$, at an ambient temperature of around –12°C, with a mass concentration of densifier, on average, of 27%. Between deep-drilling seasons, the fluid level was left at about 80 m, and no change in the fluid level between seasons was observed. By the end of the drilling, 20 drums of D-60 remained of the original number, but all drums of Solkane had been consumed, implying a total volume of 15 370 L of mixed fluid had been consumed. The theoretical column volume (from 80 m to 948 m, at diameter 129.6 mm) is 11 450 L, implying wastage of 25%. This seemed a rather high value; for example, in the 2000/01 EPICA drilling season, the wastage was 17.5% (Augustin and Antonelli, 2002). Although there was no loss from the borehole between seasons when the fluid column was left below the level of the casing, and we did not fill the borehole during drilling above the lowest level of the casing, there may have been some loss into the firn during raising of the drill, and also when adding further fluid to the borehole from a hose at the well-head, because the fibreglass casing sections were only slipped together and not bonded. All drilling chippings were collected and the fluid recovered using a Henri Petit-Jean ECO500 centrifuge and returned to the borehole. Some fluid was lost from the cable once rewound onto the drum; we attempted to catch this on a shallow plastic tray, but inevitably some was lost. Between runs, the hollow shaft was washed down with drilling fluid over an aluminium channel tray draining into open plastic boxes, and this fluid was also recovered by centrifuge and reused, though some was lost in spray.

### Generators

The electrical supply for the drilling pit (including the winch, drill, centrifuge, fume extraction fans and ice-core processing line) was supplied by a single three-phase 400 V 50 Hz (plus single phase 240 V, 50 Hz) 16 kVA model TN16K generating set supplied by SDMO. The electrical generator was driven by a 19.6 kW three-cylinder liquid-cooled diesel engine running at 3000 rpm, and the complete unit weighed 335 kg. The fuel supplied to the generator was Avtur aviation fuel, with the addition of two-stroke oil at a 50 : 1 ratio. In general, the generator consumed around 55 L of fuel per day, operating for about 17 hours $d^{-1}$. The remainder of the camp supply for leisure, messing and personal use was supplied by a range of small Honda petrol generators (single-phase 240 V a.c., 50 Hz and ranging from 0.75 to 4 kVA).

## PROGRESS OF THE DRILLING OPERATION

In all, the drilling operation from initial input of fuel to the chosen drill site (south dome, Thyssenhöhe; see Table 1 for position) to the final uplift of all equipment from the field occupied six austral field seasons. Fuel for the drilling, plus for refuelling the aircraft, as well as the bulk of the drilling fluid was pre-deployed to the site before the build-up of the drilling infrastructure and equipment. Given the volume and weight of the fuel and fluid, this was shipped to a location just to the northeast of Berkner Island in the 1999/2000 season by the BAS ship RRS *Bransfield*, then transferred to the ice shelf by helicopters operating from the UK naval vessel HMS *Endurance*, before being flown to the drill site by BAS Twin Otters. In total, 270 drums of aviation fuel, a further 20 drums of petrol and 80 drums of D-60, together with 100 ice-core boxes, were pre-deployed to the drill site before the first scheduled drilling season. Further drums of aviation fuel and the Solkane were flown in during later seasons to utilize the inbound leg of ice-core and equipment uplift flights.

The first drilling season was scheduled for 2001/02, when the planned work included the establishment of the drilling infrastructure, and the pilot borehole and casing. However, due to unusual ice conditions in the Weddell Sea, the BAS supply ship bound for Halley, carrying all the drilling cargo and part of the field team, became fast in the ice and was ultimately unable to reach and relieve Halley that season. None of the party (some of whom remained on the ship for almost 4 months) was able to reach Berkner Island.

The planned work was rescheduled for 2002/03, and this time met more success. With six people in the field, three were able to drill and sample one 80 m borehole for firn air (as a part of the European Union-funded CRYOSTAT project to sample firn air at several sites), while the other three were able to excavate a drilling trench 14 m long × 4 m wide × 4 m deep, using a combination of a small snow-blower, a chainsaw, spades and a sledge. The trench was covered by a Weatherhaven series 4 shelter, 14.6 × 4.3 m in size, though not before the mostly excavated trench was filled in by snowdrift during a storm. Once fully excavated, the floor was levelled, and covered by 25 mm plywood sheets on

**Fig. 9.** The covered drilling pit, with deep ice-core drill system.

210 × 70 mm wooden beams. In the centre of the trench, a further 4 m deep inclined trench was excavated to accommodate the tilting mast, covered by hatches in the wooden floor. A 70 m deep pilot borehole was drilled from the bottom of the hollow shaft using a shallow ice-core drill (Mulvaney and others, 2002a) mounted on the wooden floor above the trench. This pilot hole was enlarged by reaming to a final diameter of 222 mm by mounting three successively larger reamers of diameters 135, 183 and 222 mm (loaned to us by S.B. Hansen of the Niels Bohr Institute, Copenhagen, Denmark) onto the shallow-drill motor/anti-torque sections. The lowest few metres of the borehole was thus stepped down from 222 mm to the drill diameter, similar to that

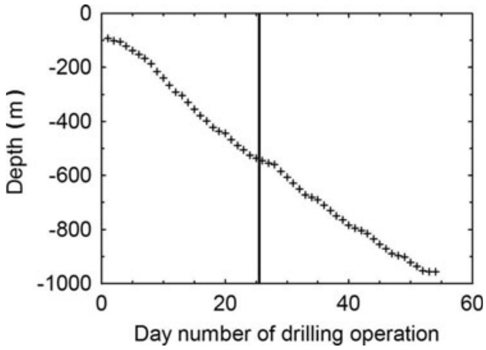


**Fig. 10.** Progress of the drilling: a vertical line marks the boundary between the two deep drilling seasons.

shown in the figure in Johnsen and others (1994). A lightweight fibre-reinforced plastic casing (200 mm internal diameter, 3 mm wall thickness and 216 mm outside diameter at the joint, 2.5 kg m$^{-1}$) in 3 m long sections was lowered down the borehole on three 1.5 mm diameter stainless-steel wires using small manual winches to 67 m depth. The sections were not bonded as planned, due to our inability to bond them in the field sufficiently straight to fit the narrow tolerance of the reamed hole. Once the casing was in place, the pilot borehole was extended to 86 m.

In 2003/04, the main ice-core drilling winch system was installed in the drill trench, and the cable loaded onto the drum using a cable tensioner to apply a load of around 300 kg when enrolling. Drilling using the new deep ice-core drill commenced after loading the borehole with the drilling fluid. Some minor problems were encountered, but in general the system performed well and as designed. The setting up of the system, together with some logistic problems, limited the drilling to a total of 25 drilling days during the season. Drilling operations (Fig. 9) lasted for 16 hours d$^{-1}$ (8 hours on Saturday), in shifts of 4 hours with four people per shift, and reached 526 m depth.

The following season, 2004/05, had further delays, when the drilling team were delayed getting to Rothera for 3 weeks due to bad weather. A further 29 days of drilling, again with few problems, saw the drilling extend from 526 m to the final encounter with the bed on 14 January 2005 at 948 m depth.

The total drilling period using the deep drilling system was 54 days; the progress is shown in Figure 10. The mean production rate was 112 m week$^{-1}$ (including training periods at the start of each season) and the overall mean

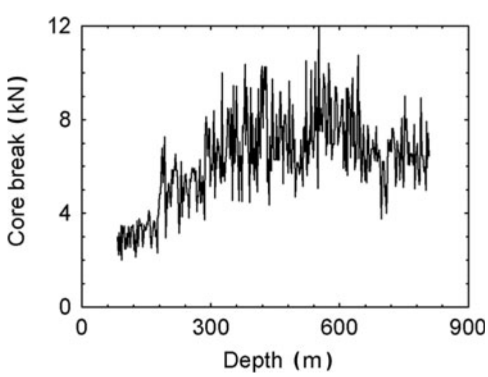


**Fig. 11.** Force used to break core at the end of each drilling run, expressed in kN.

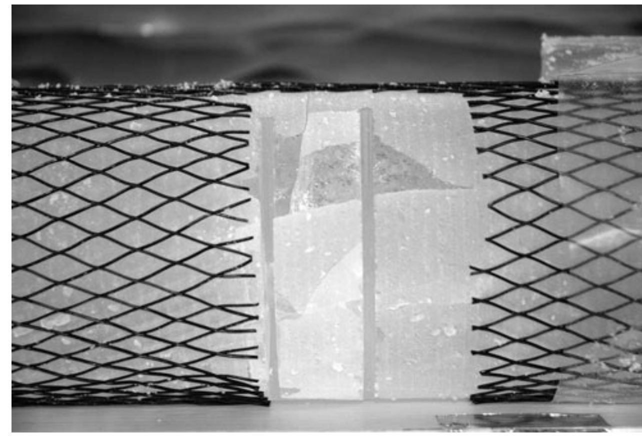

**Fig. 12.** Elastic netting used to contain brittle ice: this core from 920 m has been partially cut with the circular saw shortly after drilling in order to take a subsample, and shows the limited extent of damage to the 'brittle ice'.

core length was 1.89 m. The core breaks (after making a correction for the cable weight in the fluid) increased steadily up to around 8 kN at the 400 m depth (Fig. 11), before stabilizing between 6 and 10 kN. The core breaks decreased slightly after 650 m, corresponding to the entry into glacial ice.

Little processing of the ice was carried out in the field. A hand-held electrical conductivity meter was used to measure d.c. conductivity in the upper 450 m. At around this depth, the ice became increasingly brittle, and remained brittle to within a few metres of the bed. The cores were cut into 550 mm sections for bagging and packing in insulated boxes for transport using either a bandsaw or, more successfully in the brittle ice, a circular cut-off saw with tungsten carbide tipped blades. One innovation in the brittle ice was to push the brittle ice directly from the core barrel into an elastic plastic mesh tube to ensure that if any breakage did occur in handling, the core fragments were contained (Fig. 12). In fact, although 'brittle', the ice was never sufficiently damaged to impact a continuous stratigraphy. A rudimentary core buffer was maintained in the drill trench, and in general the cores were processed a few days after recovery. All cores were retrograded by Twin Otter and shipped in a reefer container in the same season as drilling.

The final few metres to the bed showed little in the way of visible sediment. However, the final 0.5 m of ice recovered showed a rapid change from clear ice to sediment-laden ice (Fig. 13). The transition from ice to sediment was abrupt: once the final ice core had been recovered, all subsequent runs of the drill captured no further ice, but instead large quantities of fine sand were covering the barrel and fluid pump. Several further attempts were made to penetrate the bed, but with no success beyond approximately 5 cm and at a cost of several severely worn and abraded cutters. The drilling was consequently terminated.

In 2005/06, the drill site was reoccupied and the winch system set up over the capped borehole. Using a modified Polar Ice Coring Office (PICO) manual drill barrel equipped with tungsten carbide tipped cutters mounted on a standard electromechanical drill motor and anti-torque system, we penetrated a further 50 cm into the sediment. Unfortunately, we were unable to capture a sediment core, but did succeed in recovering several kg of the basal material on the barrel

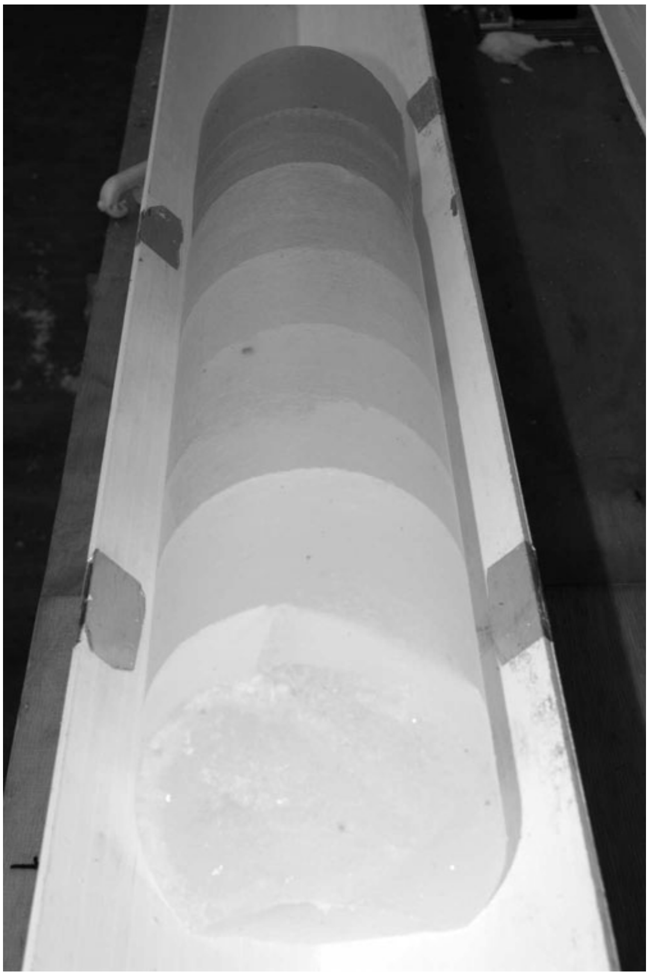

**Fig. 13.** The final 0.5 m of ice core before the basal sediment was encountered; the deepest ice is furthest from the camera. The banding is due to horizontal cracks in the core from the drilling which were not apparent on earlier cores. Below this section, no further ice was recovered, with only fine sand sediment recovered from subsequent drilling runs. Note the occasional larger conglomerate particles in the ice.

spirals, which appeared to be comprised of fine unconsolidated quartz sand. There were few 'ice chips' recovered in the barrel with the sand, suggesting we were drilling in sediment rather than ice with inclusions.

## FINAL COMMENTS

This 'lightweight' ice-core drilling project, staffed by a maximum of eight people at the drill site, successfully recovered an ice core to 948 m depth from a remote Antarctic site at almost 80° S in three short seasons, plus a fourth season for borehole measurements and basal sampling. Unusually, the sub-ice material was penetrated to a depth of 0.5 m, and basal material recovered for analysis. The drilling approach to the bed was made easier by the relatively cold basal temperature, predicted by modelling to be in the range –10 to –12°C and subsequently measured 1 year after drilling was completed as being –11.6°C (personal communication from E. Lefebvre, 2006). Although the model predicted a conservative age at the base of >30 ka, initial analysis of the stable-isotope composition of the core suggests that the bottom age is possibly >120 ka: the LGM–Holocene transition is 350–300 m above the bed.


## ACKNOWLEDGEMENTS

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THE UNIVERSITY OF WISCONSIN

**SPACE SCIENCE & ENGINEERING CENTER**

MADISON, WISCONSIN

**DOCUMENT IDENTIFICATION**

| | |
|---|---|
| Title: | **INTERMEDIATE DEPTH DRILL SYSTEM DEVELOPMENT** |
| | |
| | **ENGINEERING REQUIREMENTS** |

| | | |
|---|---|---|
| Document #: **8614-0004** | Revision: **-** | Filename: 8614-0004.curr.pdf |

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## 1.0 PURPOSE

1.1 This document outlines the engineering requirements that are consistent with the Intermediate Depth Drill System Science Requirements, REF. 3.2.

1.2 Engineering requirements for the Intermediate Depth Drill System and its sub-systems are presented in relation to the individual components that make up the complete Intermediate Depth Drill System**.**

## 2.0 SCOPE

2.1 This document applies only to the Intermediate Depth Drill functionality.

## 3.0 REFERENCES

3.1 8614-0005, Intermediate Depth Drill Design Concept

3.2 8671-0003, Intermediate Depth Drill Science Requirements

## 4.0 DEFINITIONS

4.1 **IDDO –** Ice Drilling Designs and Operations group

4.2 **UW-SSEC** – University of Wisconsin-Space Science & Engineering Center

4.3 **PI-** Project Principal Investigator

4.4 **PM –** IDDO Project Manager

4.5 **QA –** Quality Assurance

## 5.0 RESPONSIBILITIES

5.1 The project PM is responsible for ensuring that acceptable engineering requirements are created for the project.

5.2 IDDO Engineering is responsible for the creation and updating of this document.

5.3 SSEC QA is responsible for ensuring that appropriate procedures are followed for the creation, review, approval, updating and maintenance of this document.

## 6.0 ENGINEERING REQUIREMENTS

### 6.1.1 General Requirements

6.1.1.1 Drill system shall be capable of collecting science-quality ice cores to a depth of 1,500 m.

6.1.1.2 The winch shall be capable of spooling cable at an averaged line speed of ≥ 1 mps.

6.1.1.3 Ability to operate at temperatures down to -55°C.

6.1.1.4 Ability to operate to within 2°C of the pressure melting point of the ice.

6.1.1.5 Ability to drill in silt laden ice.

6.1.1.6 Drill system should be ready for testing in Greenland by 03/31/14.

### 6.1.2 Core Characteristics

This section defines the quality of the cores that will meet the science requirements.

6.1.2.1 The core diameter shall be 98±3 mm.

6.1.2.2 Minimum core length of 2.0 m.

6.1.2.3 In non-brittle ice, the packed core should have no more than 12 pieces of ice per 10 m section of core

6.1.2.4 In brittle ice, there may be a lot of pieces in a single ~2 m core segment, but the pieces must fit together retaining stratigraphic order; more than 80% of the ice volume must be in pieces that each have a volume > 2 liters.

### 6.1.3 Borehole Characteristics

The hole needs to be uniform and vertical. Post-initial core drilling operations may include logging of the hole and re-entry of the hole at later dates.

6.1.3.1 Absolute borehole depth measurement shall be 0.2% of depth.

6.1.3.2 Borehole inclination is not to exceed 5°.

### 6.1.4 Drilling Fluid

The drilling fluid assists in the cutting of the cores and balances the glaciostatic pressure of the ice. As the depth of the bore hole increases, glaciostatic pressure causes the ice to flow more rapidly back into the hole, closing it off, unless the hydrostatic pressure of the drill fluid balances the pressure of the ice. The fluid shall not dissolve the ice, or mix with any water generated during drilling. It shall also be able to be removed from the core pieces, core segments, ice chips, the drill cable, and the sonde.

6.1.5 The drill system shall be compatible with Isopar-K and/or n-butyl acetate drilling fluids.

## 6.2 Transportation

A Twin Otter or similar sized aircraft are the smallest aircraft that will be used to transport the Intermediate Depth Drill System.

6.2.1 All components should be capable of being broken down into sub-components that will fit into a Twin Otter or similar sized aircraft.

6.2.2 Volume of payload, as per the attached file titled “Twin Otter DHC – 6 Capacity”.

6.2.3 All sub-components, as defined in 6.2.1, shall require no more than 4 people to move.

6.2.4 The entire drill system shall be able to be assembled and taken down without the use of heavy equipment.

## 6.3 Core Handling

The handling of the core needs to be accomplished in a manner that preserves the cores without contamination and allows traceability of the drilling data to a specific core segment.

6.3.1 Ability to measure the length of each core to within 0.001 m.

6.3.2 Surface temperature of the core after removal from the drill.

6.3.2.1 Core temperature never to exceed 0ºC

6.3.2.2 Core temperature never to exceed -2º C for >2 minutes.

6.3.2.3 Core temperature never to exceed -10º C for >20 minutes.

6.3.2.4 Core temperature never to exceed -15º C for >1 hour.

6.3.3 Core segments to have a length of 0.90 to 1.10 m.

6.3.4 Ability to know the drilling and core handling history of each core segment.

### 6.4 Structures

The drilling operations and power generation systems must be enclosed within structures to allow operations to continue in times of poor weather and to provide protection to equipment during the winter months.

6.4.1 The drilling operations and core processing shall be housed in one structure and power generation in a separate structure.

6.4.2 Soft side tent type structures should be used.

6.4.3 Set up and take down should not require the use of heavy equipment.

6.4.4 Structures shall be capable of remaining set up for one winter over.

### 6.5 Power System

6.5.1 Diesel fuel powered generators should be used.

### 6.6 Safety

Safety of personnel on this program is paramount, due to the hazardous nature of the operations, severe environmental conditions at the drilling locations, and the extremely long travel time to advanced medical and life support facilities. Even small mishaps may have severe consequences in this environment. In addition to personnel, preventing damage to the equipment is important, because of the difficulty and cost of repairing the equipment in the field. The failure of a single piece of equipment that cannot be field-repaired could potentially cause the loss of an entire drilling season.

6.6.1 Create a safety plan that identifies hazards to personnel and equipment and defines hardware or procedural solutions to each of the identified hazards and incorporate this into the process documents.

6.6.2 Provide an analysis of mechanical/physical/chemical personnel hazards for the system and provide training and/or devices to mitigate those hazards.

6.6.3 Provide hardware protection devices that prevent damage to the equipment due to overloads in the system, such as torque limiters, over-current protection, pressure limits and mechanical fuses.

6.6.4 Safeguard the health of the drilling team while working on the system.

6.6.5 Minimize environmental impact of the drilling operations.

6.6.6 Minimize safety and health risk from exposure to drilling fluid.

6.6.7 Incorporate fluid handling and chip handling safety equipment and procedures.

6.6.8 Provide identification and protection from dangerous voltages.

6.6.9 Provide safety interlocks (Lock-Outs) to prevent the in-advertent operation of the equipment that would endanger personnel.

6.6.10 Provide emergency stop and emergency power-off systems to respectively halt and power-off the equipment in the case of an emergency. The emergency power-off systems in some cases must have fail-safe brakes such that the removal of the power will engage the brakes. (An example is the winch or tower mechanisms, which must engage the brakes and hold their last position in case of a loss of power.)

## 6.7 Operations

Operations must be done in a manner as to allow personnel to work safely and efficiently, and to be able to deal with exceptional (non-normal) cases as they arise.

6.7.1 Provide fundamental levels of operation for all equipment as needed for exceptional cases and diagnostics.

6.7.2 Provide hardware interlocks for safety and emergency operations. Co-ordinate these interlocks and operations with the other subsystems in the drill system.

6.7.3 Create an operations plan and procedures for normal drilling and surface operations of the system, and for engineering checkout of the equipment.

6.7.4 Design the drill system to be operated by 3 persons per shift.

## 6.8 Logistics

The cost of moving equipment and personnel to and from the drilling site and support of those resources is a major portion of the cost of this program.

6.8.1 Keep logistical needs and expenses at the minimal reasonable level.

6.8.2 Reduce the time needed to drill and recover cores to a minimum and maximize safety.

6.8.3 Design the system for rapid set-up and check out, and subsequent removal at the end of the season.

6.8.4 Design and provide for on-site diagnostics, repair and refurbishment of the system, including tested spares where possible.

6.8.5 Set-up time, scheduled maintenance, planned contingency time, dismantle and packing time must be included in the planning to allow meeting the science requirement, REF. 3.2, that 1000 and1500 m of core can be drilled in 1 and 2 Antarctic seasons respectively.

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# SPACE SCIENCE & ENGINEERING CENTER
MADISON, WISCONSIN

## DOCUMENT IDENTIFICATION

| | |
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| | **INTERMEDIATE DRILL DEVELOPMENT** |
| | **PROJECT MANAGEMENT PLAN** |

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## 1.0 PURPOSE

**1.1 Description of Project** – The IDPO Long Range Science Plan identifies acquisition of an Intermediate Drill as a high priority item for the US research community. The IDDO will undertake the responsibility of designing, construction, and testing of this drill.

**1.2 Responsibilities of IDDO**

1.2.1 Design of Intermediate Drill – IDDO will design the drill conforming to the requirements of document 8614-0003 (Science Requirements) and 8614-0004 (Engineering Requirements).

1.2.2 Fabrication of Drill – IDDO will fabricate one drill along with necessary spare parts.

1.2.3 Verification of Drill Performance – IDDO will verify, to the extent possible, the satisfactory performance of the drill by testing prior to the deployment of the production model(s) of the drill. A field test in Greenland is anticipated.

## 2.0 SCOPE

**2.1** This plan applies only to the design, fabrication, and verification of an Intermediate Drill. It does not apply to any subsequent field support for projects using the drill.

**2.2** This plan applies to all University of Wisconsin employees working for IDDO on the Intermediate Drill Development project. It also applies to any personnel of a subcontractor retained by the University to provide services for IDDO on the project; this would include drillers, technicians, and engineers. It does not apply to vendors that provide specified products of their own design and manufacture.

## 3.0 REFERENCES

**3.1** 1008-0002, SSEC Document Control Procedure

**3.2** 1008-0004, SSEC Change Control Procedure

**3.3** 1008-0005, SSEC Quality and Safety Training Procedure

**3.4** 1008-0007, SSEC Project Life Cycle Process Procedure

**3.5** 1008-0012, SSEC Complaint Handling Procedure

**3.6** 8501-0008, IDDO Safety Plan

**3.7** 8501-0009, IDDO Quality Plan

**3.8** 8614-0003, Intermediate Drill Science Requirements

**3.9** 8614-0004, Intermediate Drill Engineering Requirements

**3.10** 8614-0005, Intermediate Drill Conceptual Design

**3.11** PMI Practice Standard for Project Risk Management

## 4.0 DEFINITIONS

**4.1 ASSA** – Academic Support Services Agreement

**4.2** **FMEA** – Failure Modes and Effect Analysis

**4.3** **IDDO –** Ice Drilling and Design Operations

**4.4** **IDPO –** Ice Drilling Program Office, the collaboration responsible for providing planning and direction to IDDO for OPP funded projects

**4.5** **OPP** - The Office of Polar Programs of the National Science Foundation

**4.6** **NSF –** National Science Foundation

**4.7** **PI** – Principal Investigator

**4.8** **Project** – Unless otherwise noted, the IDDO project to develop – design, fabricate, and verify – a new Intermediate Drill.

**4.9** **SSEC** – University of Wisconsin-Space Science & Engineering Center

**4.10** **UW** or **University** – University of Wisconsin – Madison

**4.11** **WBS –** Work Breakdown Structure

## 5.0 ORGANIZATION AND RESPONSIBILITIES

**5.1** **Organization** – The project will be organized and executed as a project of IDDO with a formal project organization under the direction of a project manager.

**5.2** **Project Personnel –** The IDDO Intermediate Drill Development project team will be headed by a project manager who will have responsibility for the execution of the design, fabrication, and verification of the drill. He will report to the IDDO Program Director on a day-to-day basis.

5.2.1 **IDDO Management –** Program PI Charles Bentley, Program Director Don Lebar, and Engineering and Research Director Alex Shturmakov will provide overall project direction. Bentley as PI will be the main link between IDDO and IDPO and as such will ensure the IDPO is properly informed of the status of the project. Lebar as Program Director will arrange for necessary resources for the project while maintaining the project within the broader context of the FFY 2011-2014 budgets and the objectives of IDPO and IDDO.

5.2.2 **Project Manager** – Alex Shturmakov, IDDO Engineering and Research Director, will serve as Project Manager for the Intermediate Drill Development Project. The Project Manager is responsible for directing the day-to-day activities of the Lead Engineer, other IDDO staff assigned to the project, and any subcontractors engaged in the project in a manner that ensures that the science requirements are met. He will monitor and control the activities of the project using the project schedule and the budget; he will update the schedules and budgets as necessary.

5.2.3 **Lead Engineer –** Jay Johnson will function as the Lead Engineer for the project; he will also serve as a mechanical engineer on the project. His responsibilities include coordinating the efforts of the engineers to ensure that all technical aspects are integrated into the design and ensuring that the design addresses the engineering and science requirements. The Lead Engineer will also be responsible for overseeing the fabrication of the prototype of the drill developed on this project. He will also be responsible for verifying that the drill meets the performance requirements prior to its delivery to the field project PI. The Lead Engineer will report to the Project Manager.

5.2.4 **Project Engineers –** Engineers from the IDDO engineering staff and possibly contract engineers will be assigned to assist with various aspects of the development process including mechanical and electrical design, materials procurement, and testing.

5.2.5 **Field Project Support Manager** – Kristina Dahnert will assist the project team in arranging for the testing of the drill in the field and in defining logistical constraints.

5.2.6 **SSEC Quality/Safety** – While IDDO management has overall responsibility for safety and quality for the project, the SSEC Quality/Safety group plays a key role in the IDDO safety and quality efforts. The SSEC Quality/Safety Coordinator or the Quality/Safety Manager will assist the project team in developing, implementing, and documenting quality and safety plans and procedures for the project.

**6.0 PROJECT WORK BREAKDOWN STRUCTURE (WBS)** –A formal WBS will be developed for the project and defined in a Work Break Down Structure Dictionary that well be treated as a controlled document.

## 7.0 SCHEDULE

A detailed schedule based on the WBS will be developed and maintained by the Project Manager. The schedule along with the associated budget and allocation of resources will form the basis for monitoring and reporting progress on the project. Major milestones and the associated deliverables are found in the following sections.

### 7.1 Milestones and Deliverables

7.1.1 **Milestones –** The development of the Intermediate Drill must be completed and tested to the extent possible prior to being shipped for production drilling. Dates for the expected completion of major tasks of the drill's development are shown in the table below. The Project Manager and Lead Engineer for the project will establish a more detailed schedule for the project as needed.

| **Milestone Description** | **Expected Completion Date** |
|---|---|
| Finalize Science Requirements | Completed 8/22/11 |
| Complete the Feasibility Study | Completed 6/23/11 |

| | |
|---|---|
| Revise Engineering Requirements and issue the formal SSEC document | 11/30/11 |
| Revise Conceptual Design and issue the formal SSEC document | 11/30/11 |
| Complete Detailed Design | 08/31/13 |
| Complete Fabrication of the Drill | 08/31/13 |
| Complete Operating and Maintenance Documentation | 12/31/13 |
| Complete Field Test Plan | 01/31/14 |
| Complete Field Testing including Test Report | 06/31/14 |
| Complete Necessary Modifications | 08/31/14 |

### 7.2 Deliverables

7.2.1 Science Requirements **-** The IDDO PI and the Project Manager are responsible for reviewing Science Requirements that must satisfy the needs of the researchers. The Science Requirements will be a controlled IDDO document.

7.2.2 Engineering Requirements – The science requirements will be translated into engineering requirements. These are the general engineering specifications for the drill and ultimately determine the design, verification, and operation of the subsystem. The engineering requirements must address all the science requirements as well as any logistical or other constraints. The Engineering Requirements will be a controlled IDDO document.

7.2.3 Conceptual Design - The conceptual design is the technical approach taken to address the engineering requirements. It will describe, in a general way, the drill and how it operates and will provide a roadmap for the more detailed design of the equipment. The concept developed must be feasible from financial and schedule standpoints as well as from the technological standpoint. The Conceptual Design will be described in a written report that will be treated as a controlled document.

7.2.4 Detailed Design –The detailed design consists of the precise layout of the drill along with material specifications, operating and maintenance procedures, etc. Some of the design effort is expected to spill over into the fabrication phase of the project. Drawings, specifications, etc. generated in the design process will be treated as controlled documents.

7.2.5 Prototype Fabrication – Once the detailed design of the subsystem or major parts of the detailed design is finalized, fabrication of the prototype can begin. The prototype will be used to verify that the design of the drill can meet the defined engineering and science requirements. As noted above some design activities will happen concurrently with fabrication activities.

7.2.6 Field Test Plan – The project team will develop a plan for the testing of the Intermediate Drill in 2014. The plan will define the procedure(s) to be used, measurements to be made, and criteria for acceptability of performance in each type of ice in which the drill is expected to be tested. The test plan will be a controlled document.

7.2.7 Operating and Maintenance Procedures – A working draft of procedures to operate and maintain the drill will be completed prior to the test season and revised and completed based on the results of the test season. The procedures should be written in such a manner as to allow a user of the Intermediate Drill, who is not familiar with ice drilling, to successfully operate and perform routine field maintenance to the equipment. A more detailed maintenance procedure for repairing and preparing the equipment for field use may be written for use by qualified personnel working in a shop environment. The procedures will be controlled documents.

7.2.8 Field Test Report – Once field testing has been completed personnel involved in the field testing will complete a report on the results of the testing including a presentation and analysis of results and recommended modifications to the Intermediate Drill.

7.2.9 Production Version of Intermediate Drill – The Intermediate Drill design will be modified based on the results of the field testing and the prototype modified or a new copy fabricated. It is anticipated that changes will be minor and that one Intermediate Drill will be issued to investigators for use during the 2014-2015 Antarctic field season.

## 8.0 BUDGET AND COST MONITORING AND CONTROL

**8.1 Budget** – The FFY 2011 budget for the Intermediate Drill Development Project includes $93,000 for the Feasibility Study. Funds will be budgeted in FFY 2012-2014 to complete all design, fabrication, and verification activities (including a field test), along with any modifications found necessary after the field test. The Project Manager will develop a detailed project budget based on the WBS that will allow the monitoring of costs and progress of the project. Cost categories are expected to include:

- UW Labor and Fringe Benefits
- Capital Equipment – Drill components falling into the capital equipment category should be itemized if known.
- Travel
- Materials and Supplies
- Services – Engineering, fabrication services, etc. provided under ASSAs or other service contracts
- Freight

- Other Services

**8.2 Cost and Schedule Monitoring** –The Project Manager will track expenditures as they are accrued on a monthly basis. Expenditures and progress on the project will be monitored and reported using earned value management techniques consistent with the practices of IDDO.

## 9.0 COMMUNICATIONS

**9.1 IDPO –** IDPO needs to be informed of the progress on the project. IDDO Management will routinely update IDPO during their regularly scheduled telephone conferences and NSF in the quarterly IDPO-IDDO reports and as otherwise needed.

## 10.0 QUALITY

**10.1 Quality Goal** – Quality is defined as meeting the needs and expectations of the customer. The quality goal for IDDO on the Intermediate Drill Development Project, therefore, is to deliver to the science community a drill system that fulfills its requirements, including logistical requirements.

**10.2 Responsibility for Quality** – Each member of the entire project team is responsible for the quality of the product with the Project Manager having overall responsibility. In addition, the Quality/Safety Manager or his designee has the responsibility to independently monitor the execution of the project to ensure that proper procedures are followed and quality issues are addressed.

**10.3 Quality Control** - The purpose of quality control is to prevent or correct errors in the process before the product is made available to the customer. In the Intermediate Drill Development Project, control of quality will be exercised throughout each of the phases. This is done by monitoring the output of the design process, monitoring the products of subcontractors and vendors for conformance to specifications, and monitoring the execution of plans and protocols developed for testing. Quality deficiencies will be corrected in a manner appropriate for the circumstances (accept as is, reject, or modify).

10.3.1 Control of Design Quality - Design and design document reviews are the primary means of controlling the quality of the design work. Based on design review, a Failure Mode and Effects Analyses (FMEA) for the drill will be conducted. As drawings, specifications, etc. are produced, they will be reviewed and approved by the Project Manager, the Quality/Safety Manager or his designee, the Drafter/Designer, and the Lead Engineer. These documents will be controlled. During the development process, the project team will assess the design against the engineering and science requirements:

10.3.1.1 Concept Review – Upon completion of the conceptual design of the Intermediate Drill, a review will be conducted to ensure that the concept addresses the science and engineering requirements. The review panel will include at least one engineer from outside IDDO and not directly involved in the project and at least one representative of the science community selected by IDPO. Upon review and approval of the concept by the panel, a report describing the concept will be completed and approved as a controlled document.

10.3.1.2 Design Review – At the completion of the detailed design of the Intermediate Drill, a review will be conducted to affirm that the design is complete, correct, meets the science and engineering requirements and is consistent with the approved conceptual design. The review panel will include at least one engineer from outside IDDO and not directly involved in the project.

10.3.1.3 Pre-Ship Review – Prior to the shipment of the Intermediate Drill to the field for testing, a review panel that includes at least one engineer from outside IDDO with no direct involvement with the project will verify that:

- The system is complete.
- Results of any testing completed were successful.
- All issues that may have arisen during the design review have been addressed.
- All risk items have been properly mitigated.
- Spare parts are available.
- Overall, the system is ready to be shipped.

10.3.2 Control of Subcontractor and Vendor Products – Review, inspection, and testing are the methods to be employed by the project team to ensure that the work products of the various subcontractors and vendors meet defined specifications and scope-of-work requirements. "Knowledge products" such as analyses or designs will be reviewed to ensure that the product is correct and the tasks defined in the scope-of-work have been completed. In the case of components and fabrications, testing will be done where critical and practical. Inspection will be done on all components to the extent possible. With equipment or materials that are difficult or costly to test, the vendor or subcontractor's "certified" product specifications will be measured against the design specifications.

10.3.3 Verification – The project team will test the assembled prototype drill system to the extent possible to verify that the design and fabrication meets the Engineering Requirements and the Science Requirements. A formal test plan will be developed along with test procedures and used in the testing. Testing will be done timely so that all deficiencies can be corrected prior to the shipping of the drill system being issued to investigators for regular use on science projects.

**11.0 SAFETY -** The health and safety of individuals involved in the development, subsequent production and operation of the Intermediate Drill system is the requirement of highest importance. Of secondary importance is the safety of the drill system and its components. While safety is an aspect of quality, IDDO believes that safety should be emphasized in the planning process in order to ensure that the drill system is designed, assembled, tested, and operated in a safe manner. The protection of personnel and equipment is approached in two ways:

- Eliminating or reducing the likelihood of a hazardous condition by design.
- Minimizing the severity of the adverse consequences if an incident occurs by controls, training, and design to reduce propagation of problems.

**11.1 Safety Responsibility –** As with quality, safety is the responsibility of the entire Project Team and everyone associated with the project. The Project Manager has overall responsibility for safety. The Quality/Safety Manager will have the responsibility to assist the project team with ensuring that the aspects of the system they are involved with are safe and will have the responsibility for oversight of safety for the entire project.

**11.2 Control of Project Safety** – IDDO will take actions to ensure that safety is addressed as the highest priority in every phase and in every aspect of the project.

11.2.1 General Safety – IDDO expects that all Project Team members – UW employees and subcontractors – will follow the safety guidelines and procedures of their respective employers during the course of the project. These procedures include driving, equipment operation, storage and handling of chemicals, fire prevention, general behavior, etc. Subcontractors as well as UW employees are expected to follow project safety procedures while on project sites.

11.2.2 Safety During Design Process – The safe operation and maintenance of the drill system begins in its design. Two distinct safety-related activities take place during design: review of design safety and the development of operating and maintenance procedures. The project team with the assistance of the Quality/Safety Manager or his/her designee will conduct FMEA or similar analyses for the drill. The analyses and review processes will continue throughout the project as changes are made to the system. Objectives of the analyses include:

- Identification and avoidance of hazards to personnel and equipment or the minimization of the impacts of the hazard if unavoidable.
- Ensuring compliance with applicable codes and standards.
- Resolution of any outstanding issues previously identified.
- Reduction of rework.
- Better understanding of the system that can be used in the development of operating and maintenance procedures.

While the Intermediate Drill is expected to be relatively simple, operating and maintenance procedures will be developed. Of major concern in developing these plans and procedures is the safety and health of on-site personnel as well as the protection of the science experiments, the camp, and the drill equipment from damage. Where appropriate, specific actions designed to ensure personnel safety and health will be prescribed with checklists and other methods to help ensure compliance with the procedure.

11.2.3 Safety - During the Procurement and Fabrication Phase – Any hazards associated with the drill design that become apparent during the procurement or fabrication processes must be addressed. Safety requirements are to be incorporated into specifications when possible and compliance to these requirements must be checked and addressed during the inspection/acceptance process. Individuals finding situations they consider hazardous must initiate an ECN or complaint, so the design issue can be addressed in a systematic manner. Non-conformance to safety-related specifications not arising from a problem with design must be addressed and corrected in the same manner as other non-conformance items.

## 12.0 PROJECT RISK MANAGEMENT

The Project Manager will develop a process tailored to the requirements of the project to manage risk. The process should include:

- Definition of the risk thresholds
- Definition of rules for managing project risk
- Identification of risks and their owners
- Analysis of risks – both quantitative and qualitative
- Strategies, timing, actions, for responding to risks
- Monitoring and reporting risks and their mitigation

## 13.0 Reporting

The Project Manager will report monthly on the status of the project. These reports will be in the format used by IDDO to report to IDPO and will be forwarded timely to the Program Director for inclusion with the monthly report to IDPO.

## 14.0 RECORDS

**14.1 Controlled Documents –** The following documents shall be considered controlled documents and managed in accordance with 1008-0002, SSEC Document Control Procedure:

- This document, Intermediate Drill Development Project Management Plan
- Science Requirements
- Engineering Requirements
- Conceptual design document
- All schematics, fabrication drawings, and specifications

- Hazard Analyses (FMEA)
- Operating Procedures for the Intermediate Drill
- Maintenance Procedures for the Intermediate Drill
- Test plans and test results
- Any project-specific procedures judged to be appropriately classified as a controlled document by the Safety/Quality Manager and the Program Manager.

**14.2 Uncontrolled Documents** – The Program Manager will maintain the following records and documents in the project file for the entire period UW has the IDDO cooperative agreement.

- Correspondence with the Science PI and IDPO concerning the project
- Reports on project progress and expenditures
- Meeting notes
- Copies of any Complaint/Incident Reports

Copies of the records should also be archived in the SSEC (Schwerdtfeger) Library after the end of the IDDO cooperative agreement.