Mem. Natl Inst. Polar Res., Spec. Issue, 56, 196–205, 2002

Ice core drilling complications

V.S. Zagorodnov[1], L.G. Thompson[1], E. Mosley-Thompson[1] and J.J. Kelley[2]

[1]*Byrd Polar Research Center, The Ohio State University, 1090 Carmack Rd, Columbus, OH 432210, U.S.A.*
[2]*Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, AK 99709, U.S.A.*

Abstract: A common fear for all ice drillers is a stuck drill. A less severe but important concern is a foreign object in a borehole, deflected borehole or slush formation in a borehole filled with an ethanol-water solution (EWS). Prevention is the most efficient way to avoid troublesome situations. However, should these problems arise it is important to be equipped with safe and efficient tools. A stuck drill occurs rather frequently but it is rarely serious. Electro-mechanical (EM) drills usually become stuck due to inefficient chip removal from the kerf. When the drill gets stuck there are several possible actions. The simplest initial approach should be sharp jerks with a reverse rotating core barrel. Many times the Byrd Polar Research Center (BPRC) dry hole EM drill has been successfully recover using this technique. When this technique fails, another solution to the problem is to pour a few liters of auto-antifreeze into the hole using a rubber hose to bypass the upper firn. This usually frees the drill in less than one hour. In 1999 the cable on the BPRC EM drill broke, but we successfully recovered the drill from 110 m depth using 'fishing tool'.

Ethanol thermal drills also experience complications. In order to free a thermal drill when the main heating element has failed, a second heating element can be turned-on by switching the polarity of the power. There are a number of reasons why slush can form and clog a borehole. This paper presents a field proven technique for the EWS concentration correction at any depth in the borehole. Directional drilling (DD) techniques can be used to resume drilling if the drill or foreign object cannot be removed from the borehole.

This paper discusses how to recover a drill with a broken cable and describes techniques that may be used to prevent cable suspended drills similar to the BPRC dry hole EM drill from becoming stuck. The paper discusses how to maintain the correct EWS concentration and general drill design safety options.

1. Introduction

Drilling complications can arise as a result of drill operator's mistake, drill malfunction, accidental fall of a foreign object into the borehole, unexpected drilling conditions and appearance of solid particles in the kerf. Presence of a small foreign object in the kerf may considerably slow down the drilling or even cause the drill to get stuck. Solid particles and stones frequently embedded into the ice near the glaciers' bottom may seriously affect ice-drilling protocol. Preventing objects from dropping into the borehole has to be considered when design the drill setup. Also, a special tool for removing the drilling tool or foreign objects from the kerf is essential for deep drilling. Properly designed and well-prepared drill is imperative to a successful drilling operation.

The best prevention of a stuck drill is using a drilling protocol suitable for the specific drilling conditions. Violations of the drilling protocol are not rare, unfortunately. Thermal- and electro-mechanical drills have been lost in both fluid and dry holes. A drill stuck in the hole is not only a loss of an expensive tool, but also the loss of a borehole or a big fraction thereof. Therefore, a safe drilling protocol, preventive measures, adequate drill design and a suite of special tools are all important for deep drilling.

Generally, any type of drill can be stuck for a number of reasons, but the most common cause of dry hole EM drill stuck is chip jammed around the coring head. Usually, unexpected drilling conditions or a technical problem with the drill lead to insufficient chip removal that eventually causes the drill get stuck. Another common cause of a stuck drill is a failure of antitorque system and accumulation of shavings on top of the outer jacket. The higher the temperature of ice and ambient air the easier it is for the ice chip to stick together and to the drill surfaces. Drilling of polar ice below 100 m depth required slow penetration that can lead to production of fine cuttings that tend to adhere to passageways and reduce the capacity of the chip removal system.

For antifreeze thermal drilling (Morev and Yakovlev, 1984) knowledge of ice temperature is required for efficient drilling fluid usage. Often such information is not available. Furthermore, the conditions at the drilling site may be different from what was expected. Therefore, the lack of knowledge or technical problems leads to complications in the drilling protocol.

When a drill or another object is stuck in the borehole and not recovered, drilling can be continued if the shaft could be deflected off the obstacle. The directional drilling (DD) technique can be applied to go around the obstacle and resume drilling. There are a few known accidents when the drill got stuck at a substantial depth and it was worth the efforts to try to continue drilling. Quite a few such operations were successfully conducted during almost thirty years of drilling at Vostok station in Antarctica. One option is to place a whipstock or a wedge on top of the obstacle, deflect the drill and resume drilling. Our practical experience is limited to passing a hot point drill at the depth of 368 m and a successful deflection of a thermal ice core drill in an ice well (Zagorodnov *et al.*, 1994b). Here we use knowledge obtained during these experiments to speculate on how to improve that technique with respect to thermal and electro-mechanical drilling.

In general, it is better to be prepared for complications even with a well-tested drill, rather than invent a tool using scrap metal and duct tape at remote field camp. It is good to remember that such inventions could cause more problems during drill recovery than the original problem. This paper describes problems experienced by authors at polar (Central Greenland), subpolar (Eurasian Arctic) and temperate (Mt. Kilimanjaro) glaciers.

2. Prevention of complications

Three levels of preventive measures have to be considered: (1) drill and drilling setup design, (2) safe drilling procedure, and (3) availability of specialized tools to deal with complications.

In order to prevent a foreign object from falling into the borehole the lid must be

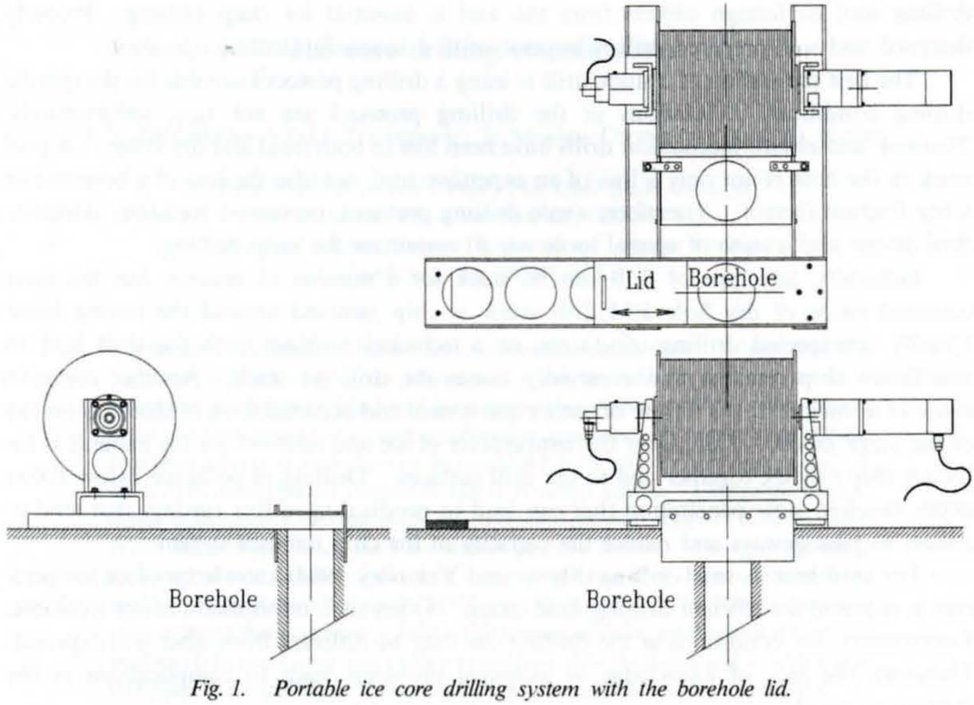

Fig. 1. Portable ice core drilling system with the borehole lid.

present at the top of the borehole. One of design goals is to make a borehole cap placement quick, effortless and convenient. Figure 1 shows the base portion of a portable ice core drilling setup (Zagorodnov *et al.*, 2000). Here the borehole interface constructed of an aluminum channel. The side plates prevent objects from falling into the borehole from under the setup frame. The cap is made of 6-mm aluminum plate and slides inside of the channel. The cap is moved in-and out of the opening by foot and does not require additional effort to position. Having a deep or trench around the top of the borehole (Blake *et al.*, 1998; Johnsen *et al.*, 1980; Zagorodnov, 1989) increases the probability of dropping a foreign object into the borehole. Restricted access to the top of the borehole and zipped pockets on driller's and visitor's dress is also a good practice.

Certain drill design options have to be taken into account as preventive measures. Inevitably, big and small objects sometimes fall into the borehole. If the cable suspended tool has a cone on top of it (Fig. 2A) the foreign object may jam the drill. If, on the other hand the drill has a flat top or a basket (chip collector) (Fig. 2B) then there is a good chance that the object can be trapped and removed from the borehole when the drill is raised.

It seems logical to consider a few weak points in drill structure. Because the most probable cause of stuck a drill is the coring head, the connection of the coring head to the core barrel can be made weaker than other couplings. The second weak point can be coupling above the widest section of the drill. And the last weak point has to be the cable termination. Obviously, the upper couplings should be stronger than the lower ones. A cable-cutting device can be an alternative for the cable termination weak point. To avoid

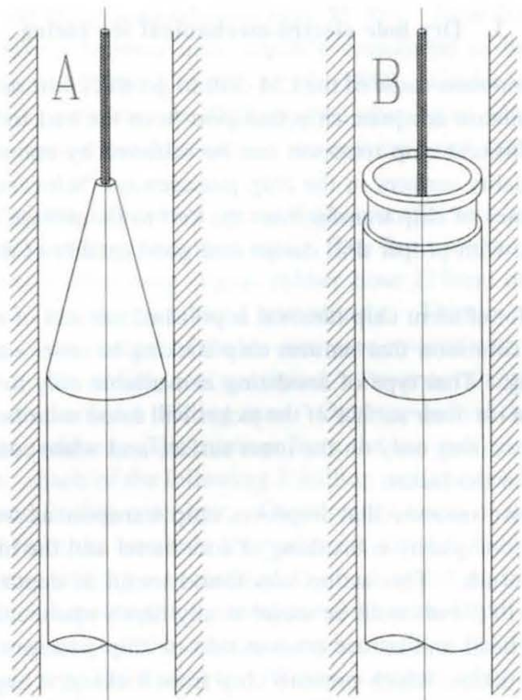

Fig. 2. Schematic of the ice core drill upper end: A-not recommended; B-recommended; details in the text.

accidental drill damage the strength of the weak points should exceed the winch pooling capacity. The weak point break has to be accomplished with a cable-pulling device mounted above top of the borehole. An appropriate cable grip device must be used to pull out the cable.

Safe drilling protocol includes regular inspections of screws on the drill and removal of chip from the antitorque system. Availability of a back up power source and a hand crank on the drilling winch helps to reduce delay of drill removal from the borehole if a technical problem occurred. Lifting the drill above the kerf is the most important action in the event of a power outage.

Borehole fluid has to be regularly inspected for presence of slush. Routine borehole inclination, diameter and temperature profiling can display slow changes of borehole geometry and thermal conditions and allow one to take preventive measures to correct the drilling protocol.

Taking detailed notes and performing post-operation analysis of drilling data is a good way to improve drilling performance and safety. Because drilling operation keeps drillers busy the best way to document drilling data is to use a data acquisition system to constantly record timing, borehole depth and power used at certain drilling operations. This keeps data collection objective, accurate and does not require additional effort from the operator.

3. Dry hole electro-mechanical ice coring

As the most of common cause of the EM drill to get stuck is insufficient chip removal. It is important to maintain adequate chip transport from the kerf to the storage compartment of the drill. Efficient chip transport can be achieved by maintaining coarseness of the chip and high quality surfaces in the chip passageways (Schwander and Rufli, 1994). We found that efficiency of chip transfer from the kerf to the storage compartment of EM drill can be improved with proper drill design and good quality of drill's parts (Zagorodnov *et al*., 2000).

First condition for efficient chip removal is polished surfaces of core barrel and outer jacket. The second condition that reduces chip sticking to inner surface of the jacket is a hard coat anodizing. That type of anodizing is available only in very dark brown or black color and a coat on outer surface of the jacket will cause solar heating. It is possible to apply hard coat anodizing only on the inner surface and white conventional anodizing on the outer surface of the jacket.

Another preventive measure that improves chip transport as well as increases drill performance and ice core quality is brushing of core barrel and the inside surface of outer barrel with a nylon brush. This action was found useful at depths below 60 m at ice temperature below $-10^{\circ}C$ but could be useful at any depth where chip are sticking to the core barrel or coring head and reduce cross-section of chip passageways.

One other useful action, which prevents chip from sticking, is application of automobile antifreeze to the core barrel and the jacket's inside surface on each drilling run. This treatment is useful below 120-m depth in polar glaciers and from the surface in temperate glaciers or in any glacier if the dry hole drilling takes place at air temperatures above the melting point.

The worst case scenario is when the drill gets stuck. Usually, in cold ice at depths below 100 m the best performance of the drill is achieved at low penetration rate (<6 mm/s) that results in production of fine cuttings. The slower the penetration the finer the chip drill produces. Fine chip have a tendency to stick to the core surface, and clog chips' passageways. When the chip plaque has formed but penetration is continued the cuttings are collected around the coring head. At that point raising the drill becomes difficult. Short peaks in drill motor current are early signs of the problem. The peaks get more frequent and eventually the drill's motor stops. Often the drill operator causes this problem when try to make longer piece of an ice core. It is easy to deal with short runs than with a stuck drill.

Another potential point to get a drill stuck is a top of the outer jacket. The drill can be stuck when the antitorque slips and the ice shavings accumulate in the jacket-borehole wall clearance. This leads us to believe that the transition between the antitorque and the jacket should not have a conical shape, since that will cause a chip jam while the drill is raised.

Drilling of ice below firn-ice transition lead to a drill stuck each 5 to 10 m or 3 to 5 times per working day. In most of these cases, tugging on the cable by hands will free the drill in a few seconds. But sometimes the tugging does not work. Then the drill's motor must be turn on in the cutting direction and make a few sharp jerks. When that action does not bring success then the motor can be reversed. That action is almost 100%

successful. Usually all these manipulations take 20–30 s. Note that the BPRC dry hole EM drill does not have a hammer unit, which is considered to be a solution for such situations (Johnsen *et al*., 1980; Clausen *et al*., 1989). Under worm conditions and sunny days drill sticking problems usually happened after 2 p.m. when the air temperature in drilling shelter can reach a few degree above the melting point, leading to inefficient chip removal.

The technique described above was not always successful and on two occasions at D1 site (South Greenland) antifreeze has been used. The first time the drill was stuck at the depth of 70 m. Using a 30 m long silicon rubber hose 12 liters of auto-antifreeze were poured into the hole. The drill was freed immediately. The top and the bottom of the drill and about 0.1 m of the bottom of the ice core were covered with the antifreeze. After the drill was cleaned up the drilling was continued. Presence of antifreeze in the borehole was noticeable only on the first 6 drilling runs. Only top half of the first ice core section showed the antifreeze residues. The cuttings from the top half of that core section was filled with antifreeze. Each of the following 5 drilling runs showed less and less antifreeze residue on the drill and in chip container. Occasionally, traces of antifreeze-filled cuttings have been recovered from the borehole long after the ice core itself showed no effects of antifreeze. In that case drilling was resumed in about a half an hour.

A severe drill stuck happened in the same borehole at the depth of 110 m. That time, not only the drill was stuck, but the cable was broken right at the drill top. Ten liters of antifreeze were poured into the borehole. Within a couple of hours a fishing tool was constructed using spare drill motor as housing. Four hooks of 0.3 m length were build of a spare antitorque blades. These hooks were attached to the motor so that they could catch the top ring of the drill (Fig. 2B). Using the drilling cable this device was lowered into the borehole and after a few attempts it caught the drill. However, when the drill was almost at surface it slipped off the hook and fell down to the bottom of the borehole. The fishing tool was lowered again and this time recovery was successful. About 2.5 hours were spent for the drill recovery including time for constructing the fishing tool. Only the cable termination had to be repaired in order to continue ice coring.

4. Antifreeze-thermal drill

There are two situations that can potentially result in TD stuck: (1) burnt heating element resulted in freezing of the coring head in the kerf and (2) slush formation as a result of low concentration of antifreeze (Zagorodnov *et al*., 1994a). The first problem is associated not only with the antifreeze thermal drill but with any type of dry or fluid thermal electric drill and could happen in cold ice much faster than in temperate ice. At ice temperatures close to the melting point there is usually enough time to lift drill above the kerf, while in cold ice a few seconds after the power is lost on coring head ice starts forming around it. More efficient, fast-penetrating coring heads with open (Augustin *et al*., 1989) and semi-open (Zagorodnov *et al*., 1998) heating elements can freeze much faster compared to massive, slow-penetrating conventional coring heads.

In the case of antifreeze TD this problem was approached with injecting antifreeze solution into the kerf during penetration and a few seconds after the drill stops penetrating. Two different designs were realized: (1) spring loaded piston which allows to inject EWS when the drill stops penetration (Morev, personal communication) and (2) forced circulation of EWS through the coring head (Zagorodnov *et al.*, 1994b). Neither device completely prevents freezing and both suffer from diminished performance (Zagorodnov *et al.*, 1998). A third possible solution to the problem is an auxiliary heating element connected to the same two conductors cable as used by the primary heating element trough a set of diodes. Then if the main heating element burns out and the drill was stuck the auxiliary heating element can be turned on by changing polarity of the current.

Concentration of EWS in the borehole is a function of ice temperature at a certain depth of the borehole. If the concentration is above the equilibrium then the borehole wall is dissolved, if it is below the equilibrium then slush is formed (Zagorodnov *et al.*, 1994a). Both processes are slow and can be detected by monitoring the lowering rate of the drill. Gradual decreasing of the lowering rate is a sign that the concentration of EWS is getting low. Reaming of the constricted section of the borehole can solve the problem temporarily. However, the narrowing is usually restores. The best solution for the problem is injection of ethanol at the depth where narrowing has occurred to raise the EWS concentration to an appropriate level.

Correction of the EWS concentration was conducted in Windy Dome borehole when unexpected temperature conditions forced use of low concentration EWS. This resulted in formation of a bottleneck below 250 m. Every morning during three consecutive days the 20 m interval with the constriction was reamed by a slow descending drill with full power on the coring head. Because the constriction was forming again and again the ethanol injection device was built. The device has a fiberglass tube housing, a polyethylene sleeve container and an electric motor. The polyethylene sleeve was filled with ethanol and both ends were sealed. The bottom end of the sleeve was attached to the motor shaft while the top end was firmly connected to the housing. At a desired depth the motor was actuated and ethanol was squeezed by the rotation of the bag. In this way the EWS concentration was corrected and drilling operation resumed without necessity to repeat this procedure again. It was concluded that attempt to save ethanol while drilling with low concentration EWS was not successful.

5. Fishing tool

Two most common problems in cable suspended ice drilling are (1) broken cable and (2) lost of the drill at the bottom of the borehole. In order to deal with these problems a universal fishing tool shown in Fig. 3 has been constructed. It has thick wall aluminum housing, and four leaf springs equipped with hooks. Depending on the goal of the fishing, three configurations are possible. First (Fig. 3A) is a fishing tool to catch a drill that is steady free on the borehole bottom. Naturally, the drill has to have side clearance to let the hooks come under the neck at the drill top. It was decided that aluminum or other soft metal neck at the top part of the drill has a better chance to be caught with hardened stainless steel hooks. In the second configuration, the springs equipped with bigger hooks (Fig. 3B) to catch the broken cable in the borehole. In order to increase the chances of catching the cable a guidance arrow is placed in the center of the device. The edges of the hooks are square but not sharp and more likely will not cut the cable loaded with the drill.

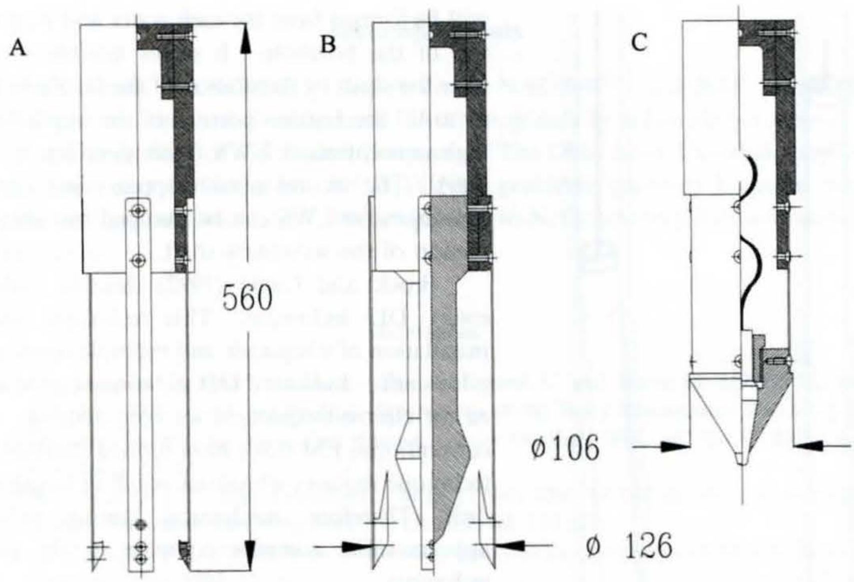

Fig. 3. Fishing tool: drill-catcher (A), and cable-catcher configurations (B), (C) hot-point drill, respectively.

Original fishing tool was developed by Morev's group (Arctic and Antarctic Research Institute, St. Petersburg) for removing solid particles from the borehole. A hot-point drill (Fig. 3C) makes a conical deep in the center of a borehole. Particles and other foreign objects fall in that deep and get removed with the next section of the ice core. Obviously, that tool can be used with any type of drill and in any glacier.

6. Directional drilling

In order to deflect drill from the bottom of plugged borehole and resume drilling it is necessary to place a whipstock into the borehole. The whipstock is a wedge device with sloped surface (Fig. 4). Removable whipstock have been constructed and successfully used in test ice well (Zagorodnov *et al*., 1994b). To deflect the drill some extra space must be provided in the borehole. Melting a cavern the size of the drill technically is not difficult, but time consuming. Using a thermal drill and a calculated protocol a cavern can be made. However, this operation can be done faster and more precisely with a special melter tool (Fig. 4). This device has electrical heater distributed in such way that the heat is directed mostly sidewise. The lower part of the device has to melt more ice than the upper part. In this way a narrow slot the width of the drill will be melted so that the drill can be deflected. The length of the melter has to be equal to the length of the drill. Estimated power of the melter is about 5 kW. Thus, melting of a 3–5 m long slot may take a few hours.

If this technique is used in the borehole filled with hydrophilic liquid then additional ethanol has to be placed at the borehole bottom. This will keep EWS concentration high enough to prevent slush formation. In the borehole filled with hydrophobic fluid slush

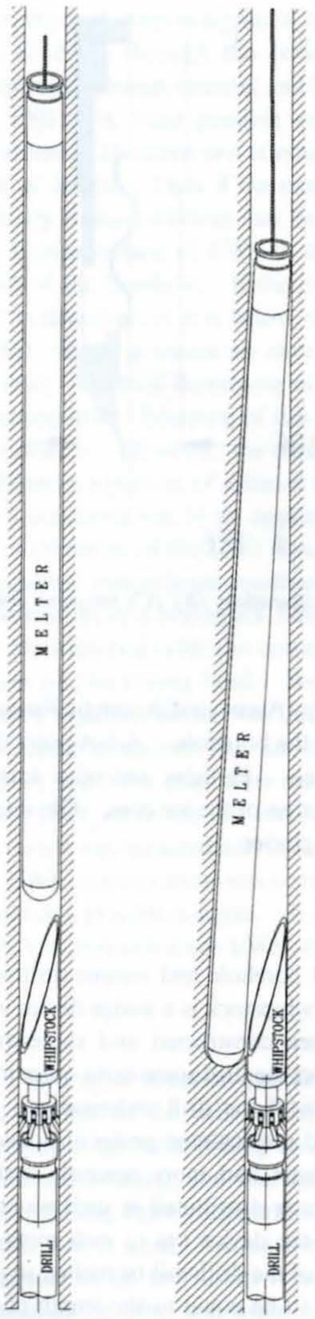

Fig. 4. Application of whipstock for passing object (drill) in the borehole.

will be formed from the melt water and float to the top of the borehole. It seems feasible to either filter the slush by circulation of the borehole liquid or to fill the bottom portion of the borehole with high concentration EWS (with densifier, if necessary). The second option appears less complex. The excessive EWS can be pumped out after completion of the secondary shaft.

Brock and Cagle (1992) describe industrial rotary DD technique. This technique includes installation of whipstock and multiple reaming of a pilot shaft. Industrial DD technique can be adopted for electro-mecahnical ice core drilling. Since conventional EM drills have limited flexibility DD technique requires whipstock equal in length to the drill. Therefore, mechanical cutting technique appears more complex compare to the melting technique.

7. Conclusions

A number of preventive measures should be considered in drill, drilling setup design and in drilling protocol. Design considerations of the borehole interface and the borehole cap can reduce the chances of dropping a foreign object into the borehole. Conical, top-oriented surfaces have to be avoided in drill design. Weak points on the coring head and cable termination may save time and resources during recovery of a stuck drill. Auxiliary heating element in the thermal coring head may also allow recovery of a stuck thermal-electric drill.

Routine borehole survey is a good preventive measure for intermediate and deep ice coring operation. Detailed record of time, depth and power for each drilling run allows one to analyze drilling protocol and make future improvements.

Whipstock installed on top of an unrecoverable object in the borehole bottom permits deflection of the drill in the cavern made by a special melter. This technique can be used with both hydrophobic and hydrophilic borehole liquids and the procedure is identical for thermal and electro-mechanical drills.

Acknowledgments

NOAA Grant NA76GP0025, NASA Grant NAGS-4075 and NSF Grant ATM-9523237 supported the drill development. Authors gratefully acknowledge support from BPRC and Department of Geological Sciences of The Ohio State University staff, especially D. Lape and F. Huffman. PICO (UNL) provided excellent logistical support during our drillings in Greenland. We are grateful to N. Gundestrup for useful comments and suggestions.

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(Received January 4, 2001; Revised manuscript accepted August 31, 2001)