THERMAL AND MECHANICAL DRILLING IN TEMPERATE ICE IN ICELANDIC GLACIERS

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ABSTRACT

A thermal ice corer was constructed in Iceland in 1968 and used for drilling a 108-m-deep hole in 1969. For shallow holes an electrical drive was added to a SIPRE coring auger in 1969 and this has been used for making a number of 10- to 20-m-deep holes.

A larger mechanical corer was then constructed for deep holes and used to drill a 415-m hole into the ice cap of Vatnajökull. The experience gained in this work and some possible refinements in the drilling technique are discussed.

Introduction

The hydrology of Iceland has been studied extensively at the Science Institute of the University of Iceland using deuterium and tritium as natural tracers. Glaciers are an important part of this study as they cover about one-tenth of the area of the country.

Initially the isotopic investigations called for shallow holes that were drilled with a SIPRE coring auger, but in order to better understand isotopic processes in temperate glaciers (Árnason, 1970) deeper holes were needed. This was solved by making a thermal corer with which two holes were drilled in 1968, an initial hole to a depth of 30 m and a second hole in the ice cap of Bárdarbunga in Vatnajökull glacier to a depth of 42 m, where the corer got stuck and could not be recovered.

The next summer a more serious attempt was made to drill a deep hole into Bárdarbunga with a new thermal corer of almost identical construction. It reached a depth of 108 m. This corer worked very well in firn but when solid ice was reached at a depth of about 30 m the drilling speed fell abruptly and the diameter of the ice core became smaller. No core was recovered below a depth of 102 m, probably because of excessive melting caused by a thick ash layer.

From this experience it was considered unlikely that a thermal corer could be used successfully for deep drilling in Icelandic glaciers.

Using a thermal corer in firn the meltwater will possibly disturb the isotopic ratio of the ice. In order to get undisturbed cores from the upper layer of the glaciers a SIPRE coring auger was used. However, it is difficult or impossible to drill holes deeper than about 5 m in temperate glaciers with the hand-driven SIPRE coring auger as one must maintain fast and even rotation of the coring auger. An electrical drive was therefore attached to the corer and with this modification it proved quite efficient for drilling to a depth of about 20 m.

Initially our interest was only for the surface layers of the glaciers but when it had been demonstrated by the combined pioneering work of Dansgaard *et al.* (1969) at the University of Copenhagen and by Langway and Hansen (1970) at CRREL that polar glaciers preserve a record of past climatic fluctuations, interest increased for deep drilling into the glaciers of Iceland. It was considered possible that the ice cap of Bárdarbunga in Vatnajökull might preserve a similar record of climatic fluctuations in Iceland since its settlement some 11 centuries ago. Such a record would be of great interest. It could be compared to considerable information in written records for the study of the reliability of the isotopic data and eventually used to extend and implement the written record.

Finally the ice core would be of interest for various other studies: the measurement of tritium and various trace elements, the study of volcanic ash layers and the physical characteristics of the ice.

A mechanical ice corer was therefore designed and constructed with financial support from the International Atomic Energy Agency in Vienna and used to drill a 415-m-deep hole into Bárdarbunga in 1972. Because of failure in the cable the bottom of the glacier could not be reached.

This paper describes the experience gained in this work and discusses some future possibilities. It is the result of work of a team at the Science Institute of the University of Iceland as well as others. The skillful work of Karl Benjaminsson, who made most of the mechanical equipment and made an important contribution to the design, is gratefully acknowledged.

Thermal Ice Corer

A simple thermal corer described by Shreve and Kamb (1964) was generally followed. Figure 1 shows a cross section of the thermal corer. The heating element is made from a 0.6-mm-diameter heating wire that is wound tightly into a helix and then pressed into a 6-mm-wide circular groove in the heater housing with thin mica insulation between the housing and the wire. The free space in the groove is then filled with alundum cement. One end of the wire is soldered to the housing but the other end is fed through a teflon insulator in the upper annular plate of the heater housing. The plate is soft-soldered to the lower part of the heater housing. An annular thermal insulator of teflon is inserted between the heater housing and the rest of the thermal corer. The total length of the corer is 120 cm.

In the first corer a polyethylene tube was inserted inside the core tube for thermal insulation, but on two subsequent thermal corers the tube was omitted, making no apparent difference.

About 250-350 W were usually applied to the heater, this being the power that the generator could produce. The heater could withstand more power but with 600 W the useful lifetime of the heating element became too short.

This thermal corer proved efficient for drilling through firn. The drilling speed was about 2 m/hr and the core radius was only about 2 mm less than that of the heater and the radius of the hole about 2 mm larger than that of the heater. The corer was used once in Sweden to drill through firn but the drilling speed was much less than 2 m/hr as the heater melted more of the core and the diameter of the hole was larger.

When the corer reached solid ice at a depth of 30-40 m the drilling speed fell abruptly to less than a meter per hour and it varied considerably from one run to the next. The core showed clearly the reason: instead of recovering a core with a diameter of 45 mm, as was being done in the firn, the core usually had a diameter of 35 mm or less. Sometimes no core was recovered at all and the core recovery averaged less than 50 per cent.

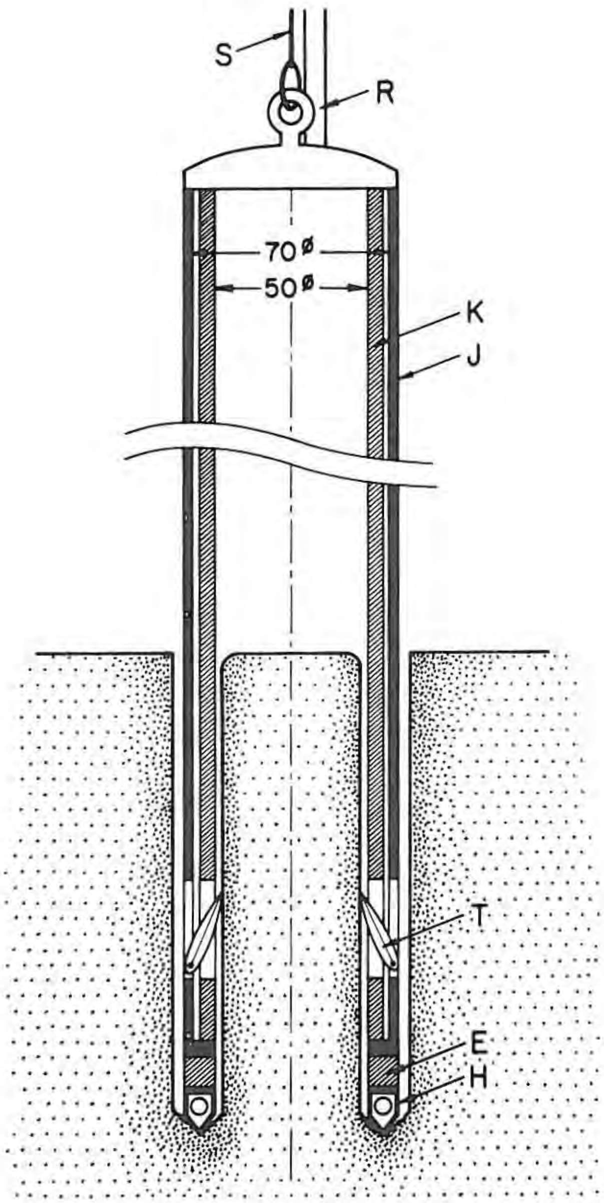

Figure 1. Cross section of thermal drill. H: heater. E: thermal insulator of teflon. T: pawl for breaking ice core. J: core barrel. K: insulating tube of polyethylene. R: cable. S: steel wire.

During a few runs in solid ice the drilling speed was quite high compared to an average run and a good core would be recovered with a diameter of 35-40 mm along its full length of 1 m. In the next run the corer would penetrate faster than normal in solid ice and produce a reasonably good core. During the drilling we were aware that there was water in the hole but we had no means to measure the depth to the water table. Some crude estimates were made by fastening pieces of tissue paper to the cable at varying heights above the corer. From a few such unsystematic observations we got the impression that the water table was usually some meters above the corer and it seemed lower when good cores were being recovered. This is, however, not in accordance with the experience of the deep drilling three years later, made about 5 km away at an elevation some 200 m lower, where the water table was very stable (discussed below).

It seemed clear that the meltwater trapped in the solid ice gave rise to convection currents at the bottom of the hole, causing excessive melting and a slow drilling rate. Attempts were made to hinder such convection currents by fastening rubber blades on the top of the thermal insulator in an effort to isolate the bottom from the rest of the hole. This seemed to have no positive effect.

When a depth of 102 m was reached the drilling speed became still slower and no core was recovered at all. Deep drilling three years later showed that a thick ash layer can be expected at this depth.

After this experience we were not optimistic about the use of a thermal ice corer for deep drilling in glaciers in Iceland. Experience in other countries indicated, however, that a thermal corer with a direct heater might yield better results. Such a corer was made together with the mechanical ice corer for drilling in Bárdarbunga in 1972. The heater consisted of a single circular turn of bare wire with a diameter of 3 mm. The diameter of the circle was 115 mm. Two short wires were soldered vertically to the circular heater and this served both for fastening the heater and as electrical leads for the low voltage supply. A 3-kW transformer was fastened to the upper end of the core barrel. This corer was tried in solid ice at Bárdarbunga but the drilling speed was very slow and this attempt was soon abandoned, along with any prospect of using a thermal corer for deep drilling in glaciers in Iceland.

Electrically Driven SIPRE Coring Auger

The SIPRE coring auger has been modified by adding an electrical drive to it. A 750-W electrical hand drill is fastened to the top rod for rotating the ice corer. The speed of rotation is 250 rpm, but this proved too fast and the speed was decreased by frequently interrupting power to the motor. About 100-150 rpm would probably be optimal.

New rods were made from thin-walled steel pipes with special connecting pieces soldered to their ends. These pieces (Fig. 2) have a rectangular cross section and the lower one fits into the upper one; the latter rests on a rim at the end of the circular pipe. A wing screw holds the two connecting pieces together and, because of the rectangular cross section, there is no strain on the screws during drilling The rods are different lengths (1, 2 and 3 m) because it is most convenient to add only 1 m to the total length of the rod string each time.

When this arrangement was first tried there was no means to center the rods in the hole and they had a tendency to oscillate and beat against the wall. To remedy this, centering pieces (Fig. 2) were put on the rods 2-3 m apart, nearly eliminating the oscillation. In this form the ice corer has been used extensively to drill 5- to 15-m-deep holes.

In glaciological work there is a frequent need to drill holes of 30 m or less and this should preferably be made with as simple equipment as possible. With further modifications the SIPRE coring auger would be suitable for this kind of work.

With the present technique it is easy to drill to 10 m but below this it becomes increasingly difficult, mainly because of the weight of the rods. It should, however, not be difficult to add a simple winch to the equipment using the same motor as for the corer.

Some kind of platform should be added, both for centering the rods at the upper end as well as for locking the rod string while adding a new rod or taking one off.

One of the most serious drawbacks of the SIPRE coring auger is that it takes only a 30- to 40-cm-long ice core in each run. Attempts to increase this have been futile. With the faster and more even rotation of the electrical drive it should be possible to lengthen the corer and decrease the width of cutting. The ice chips would then take less space and this would make room for a longer core.

The Mechanical Corer for Deep Drilling

The equipment used for drilling a 415-m-deep hole into the ice cap of Bárdarbunga in Vatnajökull glacier has already been described and some discussion of the experience using it presented (Árnason *et al.*, 1974). Some features of the drill and corer will be described in more detail here and some design considerations discussed as well as the experience gained. Some suggested improvements of the drilling equipment and corer will also be discussed.

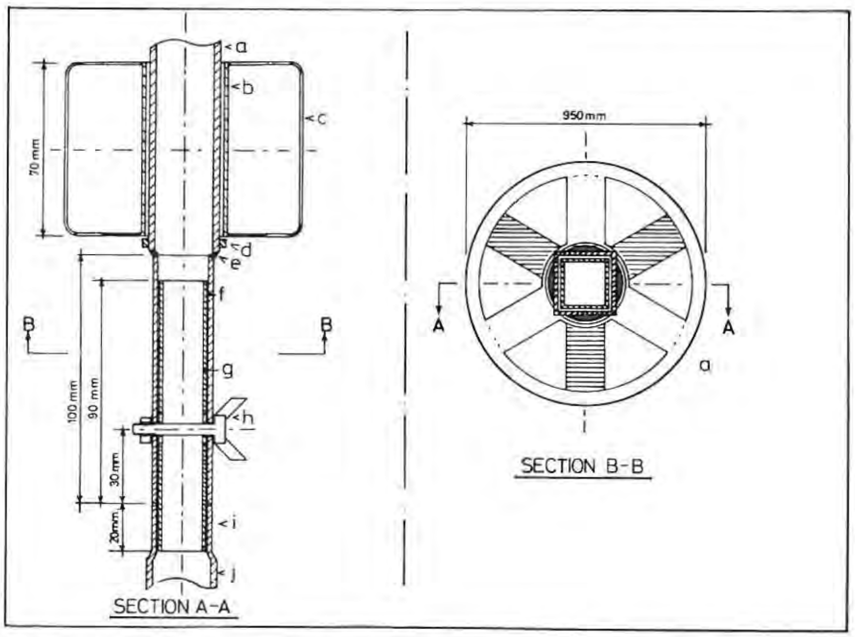

Figure 2. Connecting pieces of drill rods and centering pieces. a: circular rods. b: centering pieces. d: rim on which centering piece rests. e: soft solder. f: upper rectangular connecting piece. g: lower connecting piece. h: wing screw.

When the design of the corer began many uncertainties confronted us as we were guided by very limited practical experience. Our use of the electrically driven SIPRE coring auger gave us valuable hints and the experience the author gained in participating in an American-Danish drilling project in Greenland in 1971 was of much help.

It was of great importance to know whether there would be water in the hole because it would presumably strongly influence the transfer of the ice chips from the cutting bits. Further, if the hole would be partially filled with water this would counteract the closure of the hole that was considered to be one of the most serious obstacles to deep drilling in temperate ice.

Experience from the 108-m hole drilled with the thermal corer indicated that there would be water at the bottom of the hole most of the time after solid ice had been reached. It was therefore assumed that the drill and corer would be submerged in water after the firn had been penetrated. Some difficulties could be expected in the firn with the mechanical corer and this was partly the reason for also making a thermal corer, as experience had shown that it worked very well in firn.

Figure 3 shows a cross section of the drill and corer. Briefly, it operates as follows. A 2.0-m-long core barrel tube rotates inside a stationary outer tube. Two cutting bits on the lower end of the core barrel cut a 15-mm-wide groove into the bottom of the hole. The ice chips are carried up into the storage compartment above the core barrel by a helical rib on the barrel. After each run the storage compartment is emptied.

The total length of the ice corer is 6 m. In the *cable termination cylinder* on the top of the corer there is a strong helical spring that carries the weight of the drill and corer. A device senses the compression of the spring, indicating when the corer is resting on the bottom of the hole with more than a certain fraction of its total weight. A pin touches an insulated spring when about 70 per cent of the weight is resting on the bottom of the hole. An ohmmeter measures the resistance between the spring and the pin. Initially this was meant to be an ON-OFF device only but as the gap is filled with water when the drill and corer are in the hole the resistance begins to fall when the pin approaches the spring, indicating that the drill and corer are resting with increasing weight on the bottom of the hole. This proved to be of much additional help during drilling and has shown us that a potentiometer should replace the spring in future work to give a continuous indication of the weight on the bottom of the hole.

The *electric motor* was a 3-phase 380-V AC, 3-hp motor, but it failed and was replaced by a 3-phase 220-V AC, 2-hp motor. Both motors are of the same type and are made for submergible pumps.

A *planetary gear* taken from a starter in a DC-3 airplane (omitting one stage) was used to reduce the speed of rotation to 150 rpm. Later experience indicated that this speed was suitable. The outer diameter of the gear was the main factor in deciding the diameter of the corer.

Below the gear there are three torque skates that are pressed against the wall to prevent the rotation of all parts but the core barrel. The length of the torque skates is 15 cm. In solid ice these gave sufficient force to keep the outer tube from rotating. In firn the torque seemed to be sufficient also but the cable with its large diameter (22 mm) may have helped provide some of the torque needed. While drilling through the firn we were occupied with various minor problems so that close attention was not given to the performance of the torque shoes.

Between the torque skates and the core barrel there is a 2-m-long annular space for storing the ice chips during the drilling, the *storage compartment.* The storage compartment is emptied after each run through a hatch on the cover tube.

The *core barrel* (inner/outer diameters 91/95 mm) is 2.0 m long and the space between it and the cover tube (inner/outer diameters 106/110 mm) is only 6 mm. The ice chips are transferred during drilling from the cutting bits to the storage compartment by a pair of auger flights on the core barrel. These are made of rectangular steel bars (5x5 mm) silver-soldered to the barrel. The pitch of the flights is 20 cm at the lower end and increases to 26 cm at the upper end.

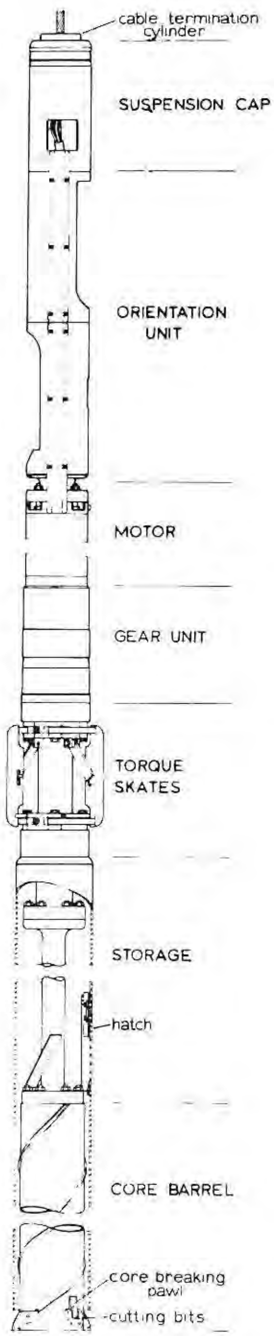

Figure 3. Cross section of the mechanical drill.

Considerable attention was given to the removal of the ice chips. The possibility of letting them float freely in the hole, which we assumed would be partially filled with water, was considered. We feared, however, that the corer might cut into a crevasse in the ice, the water would run out of the hole, and the ice chips might then clog the lower part of the hole. This idea was therefore abandoned.

The possibility of partially melting the ice chips was then considered. Water was to be circulated with the help of a pump above the core barrel and heater elements were to be inserted into the storage compartment, which was considerably smaller than in the final design. It was hoped that the stream of water would help in moving the ice chips up between the core barrel and outer tube and then divert the ice chips to the heater elements. This arrangement was also considered useful in case the corer would get stuck in the hole, as the circulation of the heated water would help in freeing the corer. Laboratory tests with a prototype indicated, however, that the water circulation helped little in moving the ice chips up into the storage compartment, so this design was therefore abandoned.

After this the corer was designed with a storage compartment large enough to retain all the ice chips from a single run and the heaters were only considered as an additional aid that might be resorted to in case the corer showed a tendency to get stuck. The length of the storage compartment proved to match well the length of the core barrel, as the ice chips were tightly packed there in the few runs when an ice core of full length (2.0 m) was drilled.

Initially there were no auger flights in the storage compartment. After having drilled in solid ice for some time the ice chips seemed to be pressed rather firmly together at the bottom of the storage compartment. A 15-cm-high (approx.) double auger flight was therefore welded to the axle just above the core barrel. No further difficulties of this type were observed.

When the corer was being designed it was first considered helpful to have the pitch of the auger flights greater at the lower end so that the ice chips would be carried more firmly away from the cutting bits. A test with a prototype of the corer showed, however, that the reverse was the case; i.e. the ice chips became clogged when they reached the point where the pitch decreased. When the pitch was changed, increasing slowly all the way up along the core barrel, this difficulty disappeared.

Two *cutting bits* are fastened with screws to the core barrel as well as a pair of core catchers for breaking the core at the end of each run.

Although many difficulties were met in the drilling work and the bottom of the ice cap was not reached, an important objective was achieved: the corer worked successfully in the last phase of the work and a total depth of 415 m was reached. The estimated thickness of the glacier at the site of drilling is 450-500 m.

Three serious difficulties were met: (1) weakness of the cable, (2) low drilling rate in solid ice, and (3) frequent sticking of the corer at the bottom of the hole at the end of a drilling run.

Creeping occurred in the braided steel armor of the cable under load resulting in the load being transferred to the copper leads which were occasionally stressed beyond the breaking point. A final break in a power lead stopped the drilling temporarily at a depth of 298 m. A new cable was borrowed from CRREL and the drilling was resumed after a delay of three weeks. The length of the cable limited the final depth of the hole to 415 m. The diameter of the hole was not measured but judging from the smooth movement of the corer no closure of the hole could be sensed. The hole was, however, filled with water below a depth of 32 m, just below the limit between firn and ice. The water level was quite stable. We once used the outer tube of the corer, after the core barrel had been removed and the lower end of the outer tube closed, to bail water out of the hole. The amount of water bailed out was equivalent to a water column of about 7 m but the water level in the hole changed less than 1 cm.

The most serious difficulty in the drilling work was the low drilling rate. A test with a prototype in the laboratory had indicated that the corer would cut through 1 m in about 5 minutes. When we were drilling through the firn, where we had anticipated some difficulties in transporting the dry ice chips up into the storage compartment, the drilling speed was satisfactory. When we reached solid ice just below 30 m the drilling speed was reduced considerably. Instead of drilling 2 m in 5-10 minutes a penetration of 40-80 cm would take 20-50 minutes and then the corer would not go deeper. Shaking the cable and turning the corer motor on and off helped considerably but to a lesser degree as the hole became deeper. As long as the drilling speed was high enough to make it likely that we could drill through the estimated 450-500 m of the ice cap, the main emphasis was on continuing the drilling.

Gradually evidence accumulated indicating that the ice chips were freezing together on the cutting bits, thus reducing and eventually stopping the drilling. This difficulty was successfully overcome by introducing an antifreeze mixture to the bottom of the water-filled hole. A polyethylene bag with about 180 ml of isopropyl alcohol was tied to the end of the core barrel. When the motor of the corer was started, the bag burst and the alcohol mixed with the water by the rotating core barrel. This lowered the freezing point at the bottom of the hole and hindered the freezing of ice chips around the cutting bits. The third major problem was the frequent sticking of the corer at the bottom of the hole at the end of a drilling run. After we started using the antifreeze mixture it would take only about 5 minutes to drill 100-140 cm. The drilling speed would then fall abruptly, presumably because the alcohol had been diluted so much that the ice chips started freezing around the cutting bits. The motor was then stopped and the corer raised 20-30 cm by turning the winch by hand. The corer would then sometimes lodge fast in the hole. In such cases a tension of about 600 kg was applied to the cable. In most cases this would be sufficient to free the corer but sometimes it would not move. We then waited until it got loose by itself under this tension. This could take up to an hour but twice we had to wait longer. Once we waited for some eight hours and the corer did not get loose until we had increased the tension by about 20 per cent.

This sticking is probably caused by the ice chips freezing together at the bottom of the hole outside the outer tube. This could probably be avoided if the drilling stopped before the alcohol became diluted so that the ice chips begin to freeze together. However, because a major part of the total drilling time was taken up by raising and lowering the drill, it was tempting to take as much core in each run as possible. Further, as the day shift was competing secretly against the night shift little time was left for experimenting during this final stage of the drilling. Therefore we lived with the problem rather than solving it.

Having discussed the major problems of the drilling some general remarks follow about the performance of the corer. The coring motor seemed to be working lightly most of the time. There was an ammeter on all 3 phases of the motor in the corer. Hanging freely in the hole the motor would take about 4.0 A. Under light load during drilling the current would rise to 4.3 A, occasionally to 4.5-5.0 A, and higher in extreme cases. It should be remembered that the load will not be proportional to the current because of varying phase difference between the voltage and current. It would have been more useful to have a wattmeter measuring the load of the motor. The load seemed to depend strongly on the weight with which the corer was resting on the bottom of the hole. The warning device, that was to show when this exceeded 70 per cent of the total weight of the corer, was inoperative most of the time because of a break in the signal leads of the cable. Most of the drilling was therefore done under unfavorable conditions. As already noted the corer got stuck at a depth of 17 m and once the motor burned out because of excessive load, presumably because it was continuously resting on the bottom of the hole with its full weight. The last 118 m were drilled with a cable borrowed from CRREL because of a break in the power leads in the initial cable. During this time the load warning device was operative and this helped much in giving smooth drilling.

Drilling Facilities and Suggestions

Good working conditions are important for prolonged drilling on glaciers. How this is solved will depend on the conditions. In our case we provided excellent working conditions by digging a large pit (7.0 x 2.7 m wide and 4.2 m deep) and covering it with a roof of polyethylene foil fastened to a wooden frame. Drift snow collected on the roof, requiring considerable work in keeping the roof free. A combination of pit and surface shelter would probably have been better.

Insufficient attention was given to the shelter for the power plant. It should have good cooling during calm weather but should be sufficiently well closed during storms so that drift snow will not make it wet. Care should be taken that the exhaust is vented so that it will not melt the surrounding snow. Finally it is useful to have some arrangement in the power plant to dry clothing. As drift snow is likely to collect around the shelter of the power plant, the plant should be on a sledge so that it can be moved easily and the cables kept free from being buried in the drift snow.

For future drilling operations, if a hole of 400 m or less is being drilled, the core barrel and storage compartment should be shortened to about 120 cm each instead of the present 200 cm.

The same method of delivering the antifreeze mixture to the bottom of the hole might be used. It would, however, be desirable to pump the alcohol continuously to the bottom of the hole during drilling, thereby probably eliminating the difficulty we experienced in freeing the corer at the end of the run. For some studies it is undesirable to add any foreign fluid to the hole. A heater on the lower end of the outer tube might solve the problem of the freezing ice chips instead of using the alcohol.

The time it takes to remove the core and empty the ice chips from the storage compartment should be shortened. It should be possible to reduce this from the present 15 minutes to 5 to 7 minutes.

The most probable of the more serious problems one can expect in deep ice-core drilling is getting the corer stuck in the hole. In such cases it is important to know reasonably well how much tension can be applied without impairing the cable and winch and have reasonably good indications of the tension in the cable. We solved this by pulling the winch handle with a spring balance. A more sophisticated arrangement would be desirable, but a spring balance should be available.

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